Title: Power spectrum of the dark ages

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Abstract: In the future it may be possible to observe the CMB radiation at very low frequencies. I review the origin of the signal from 21cm absorption by dark-age gas and explain the huge potential for observational cosmology. I summarise recent work on theoretical expectations for the observable power spectrum, including discussion of Hubble-scale perturbations, the effects of perturbed recombination and non-linear evolution.

Power spectrum of the dark ages

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Work with Anthony Challinor (IoA, DAMTP); astro-ph/0702600

Following work by Scott, Rees, Zaldarriaga, Loeb, Barkana, Bharadwaj, Naoz, ...

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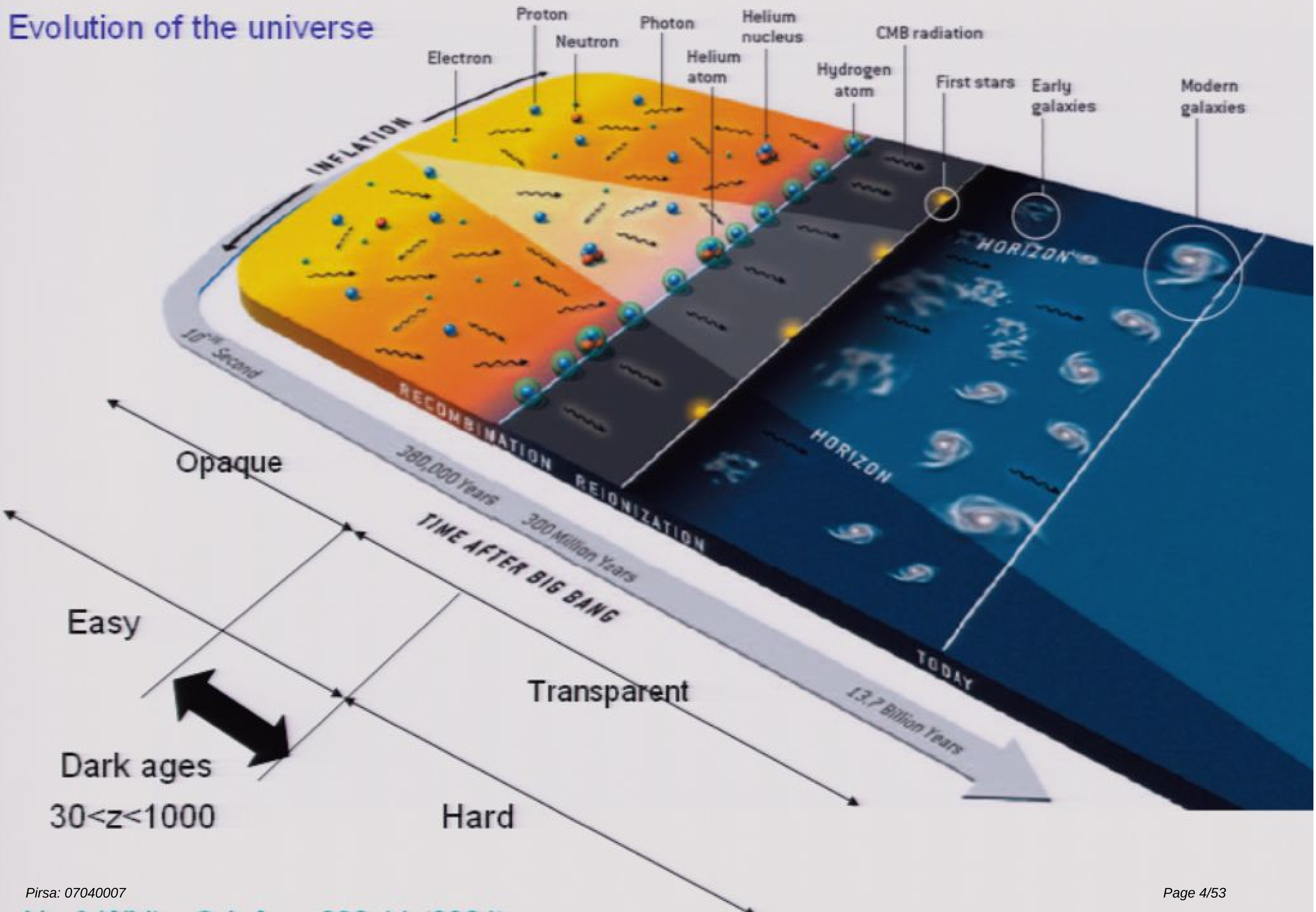
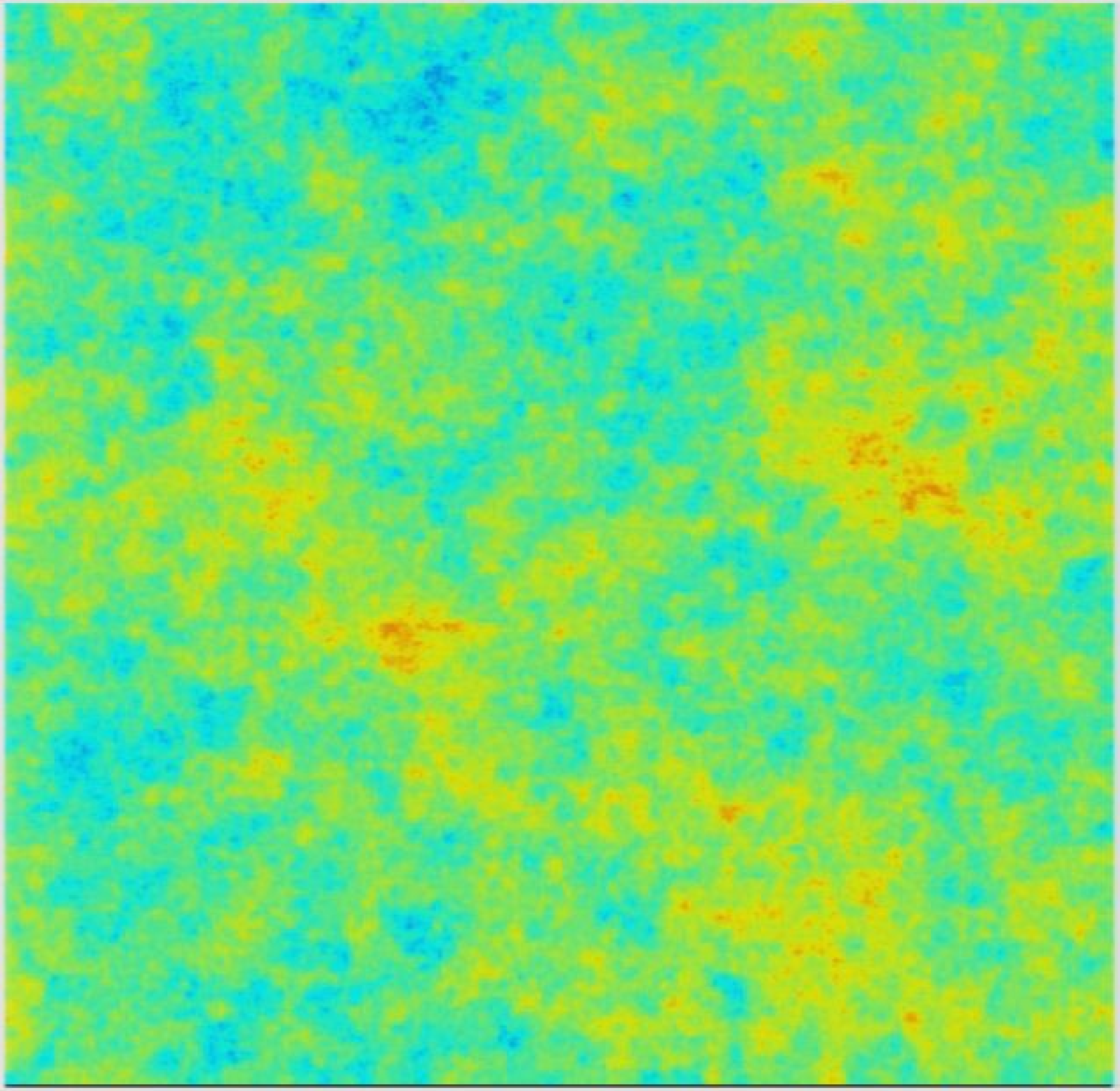
Evolution of the universe

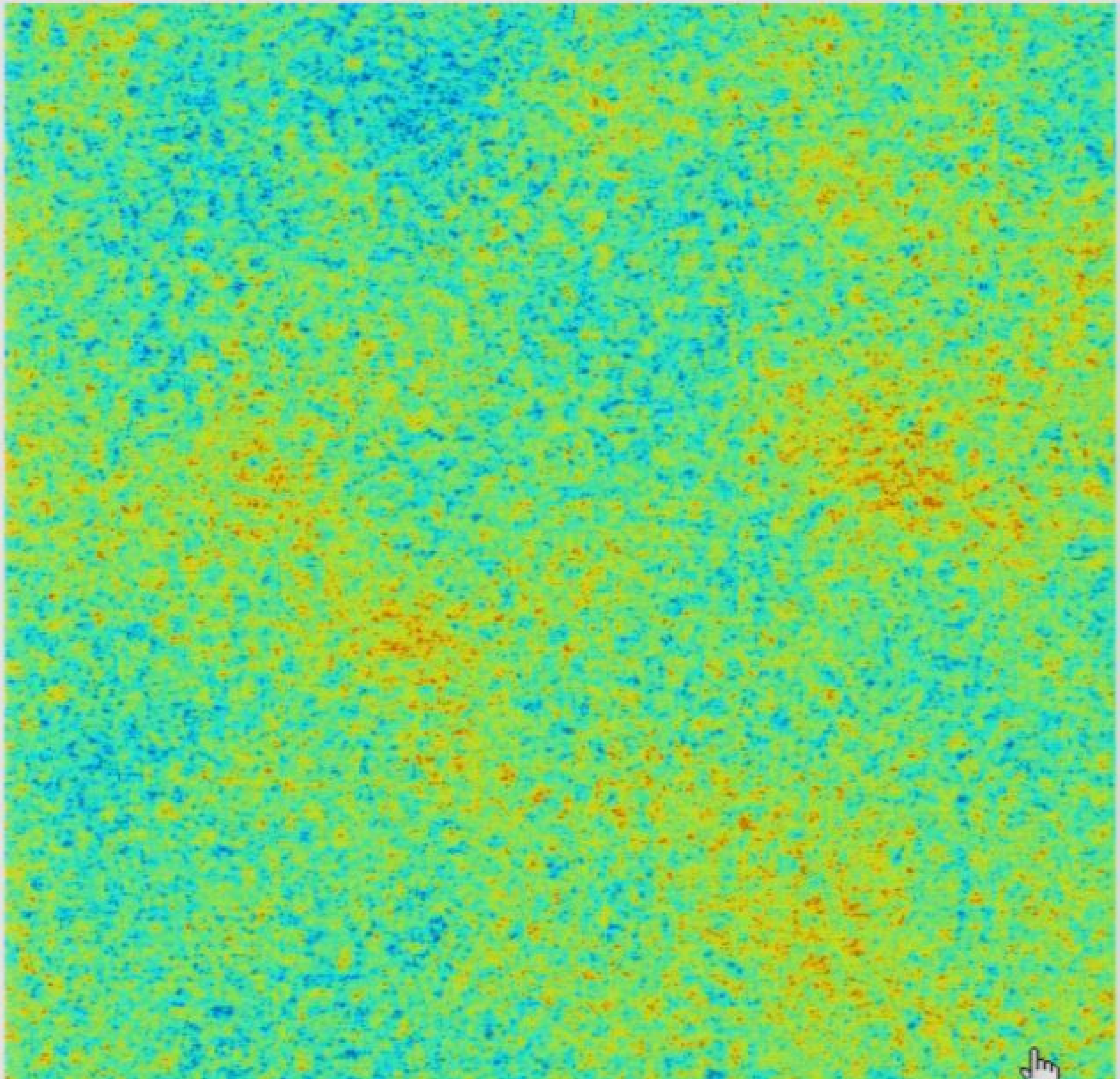


Hu & White, Sci. Am., 290 44 (2004)

CMB temperature



CMB temperature



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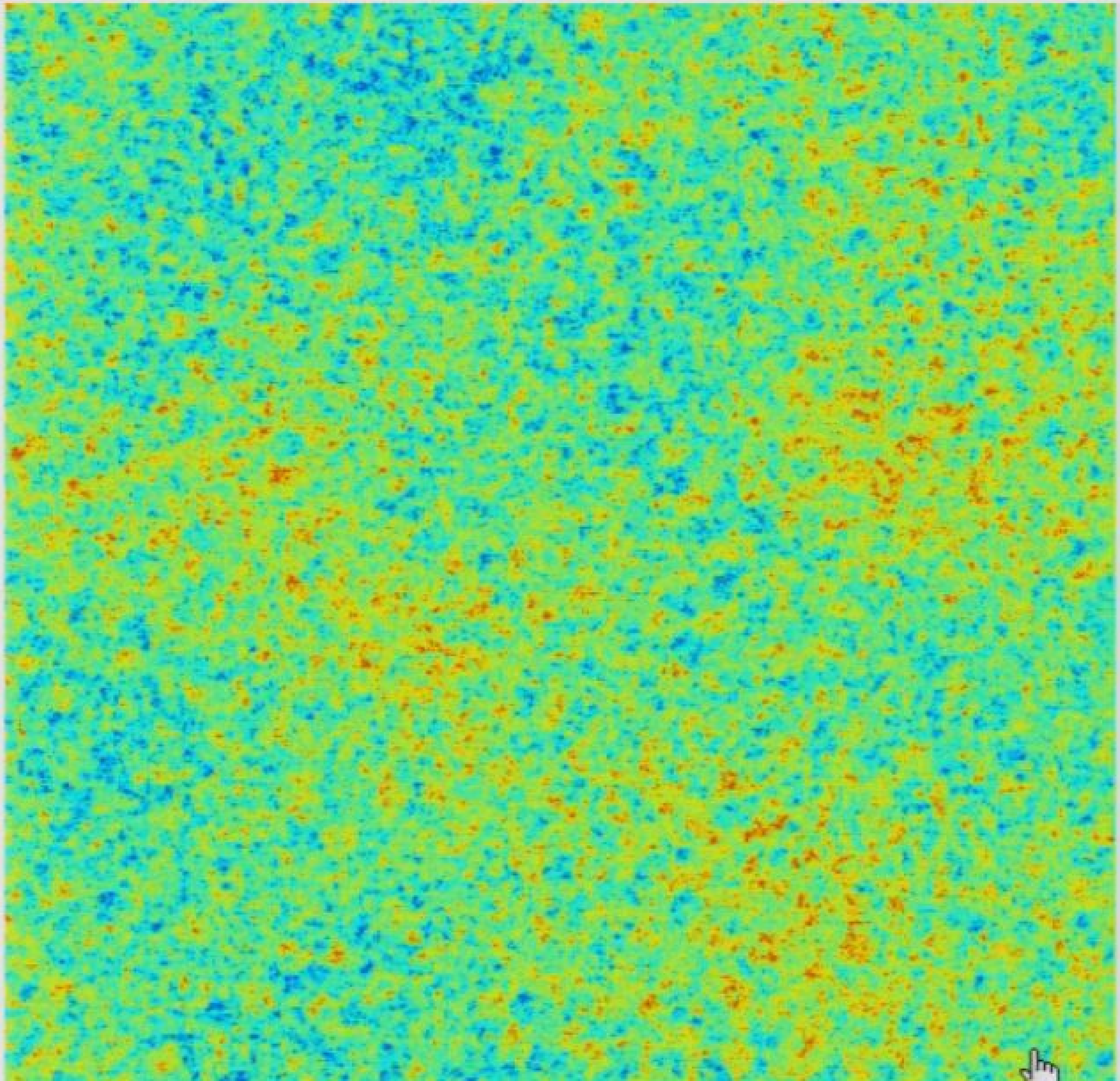
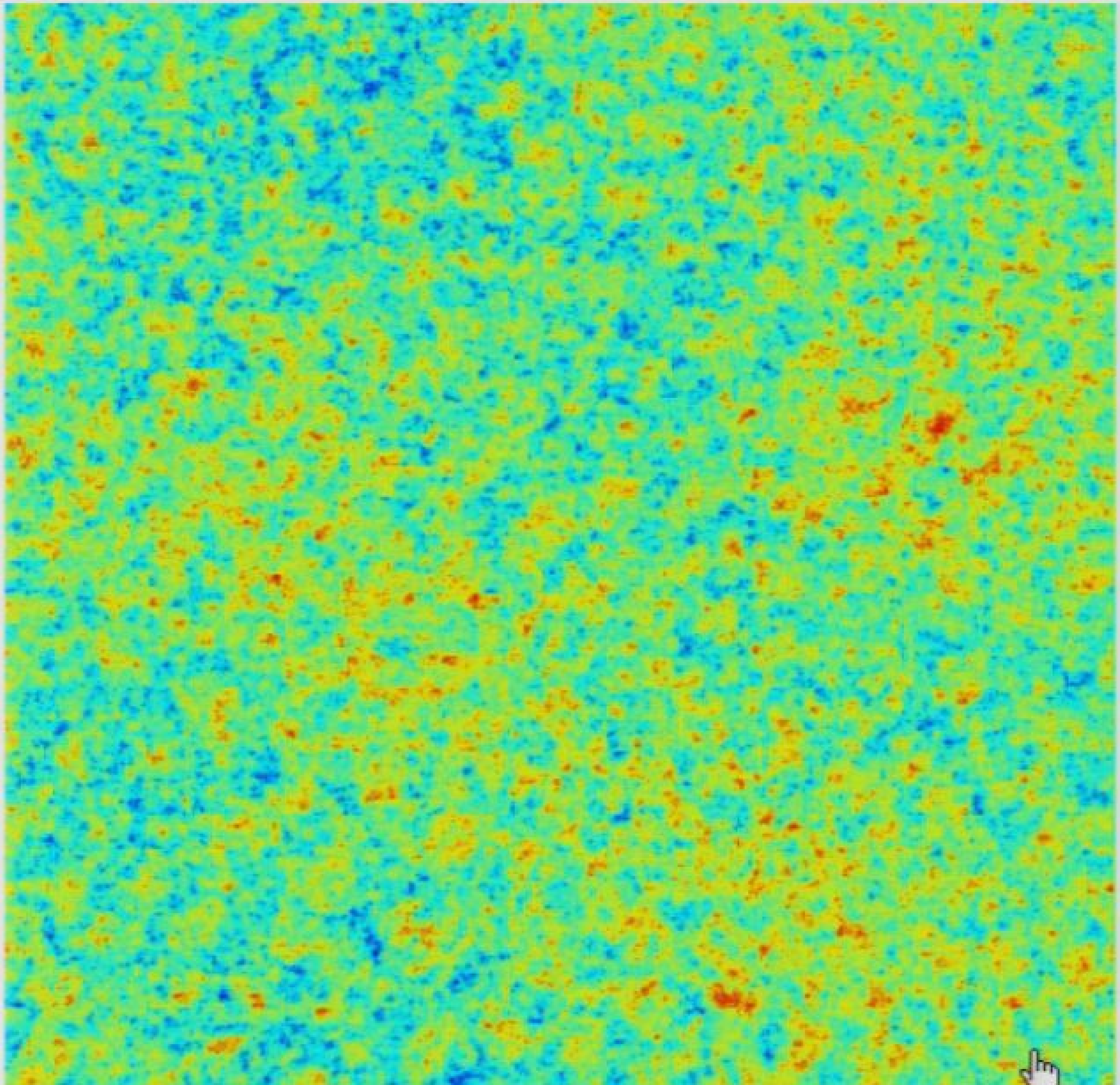
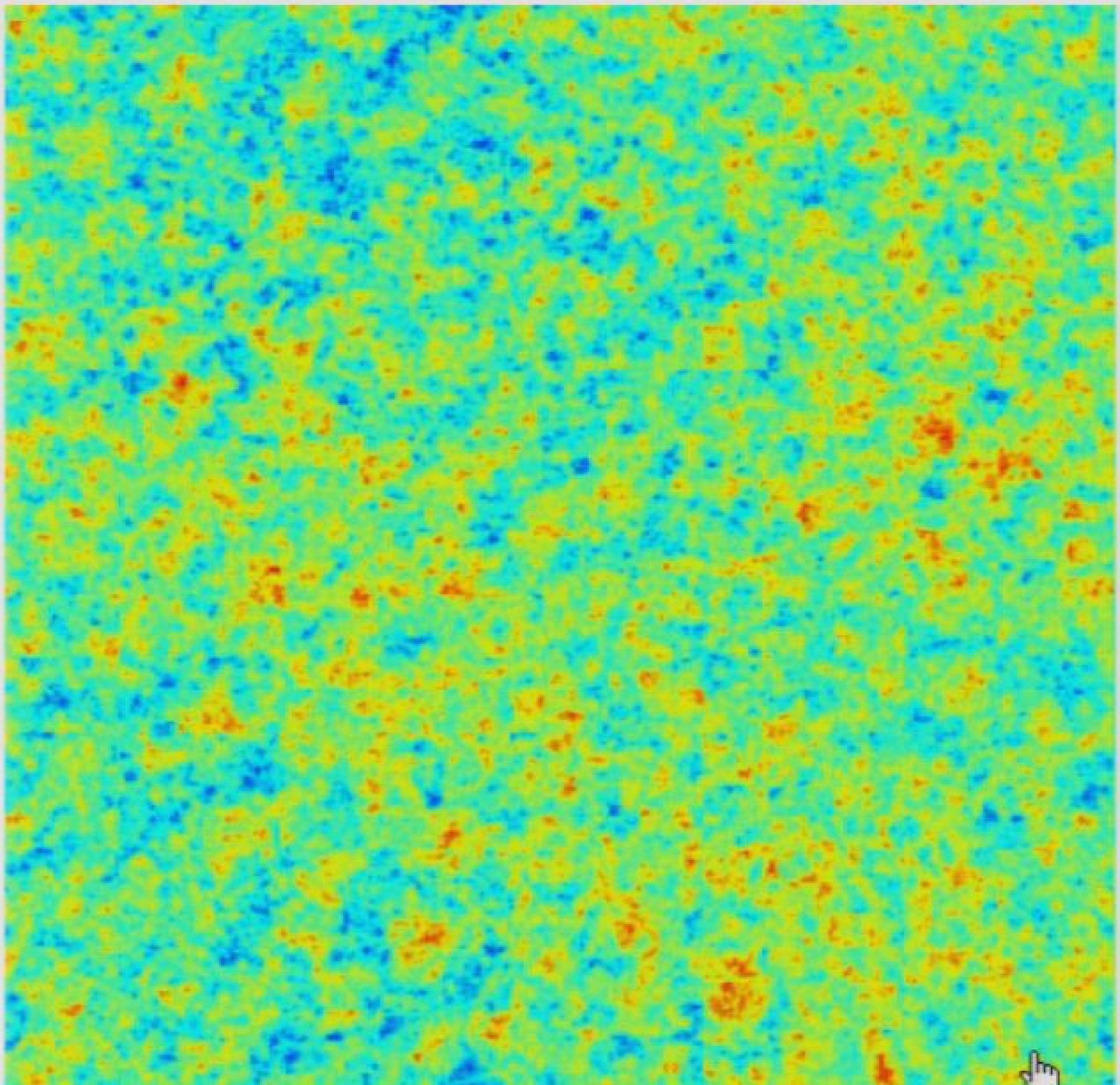


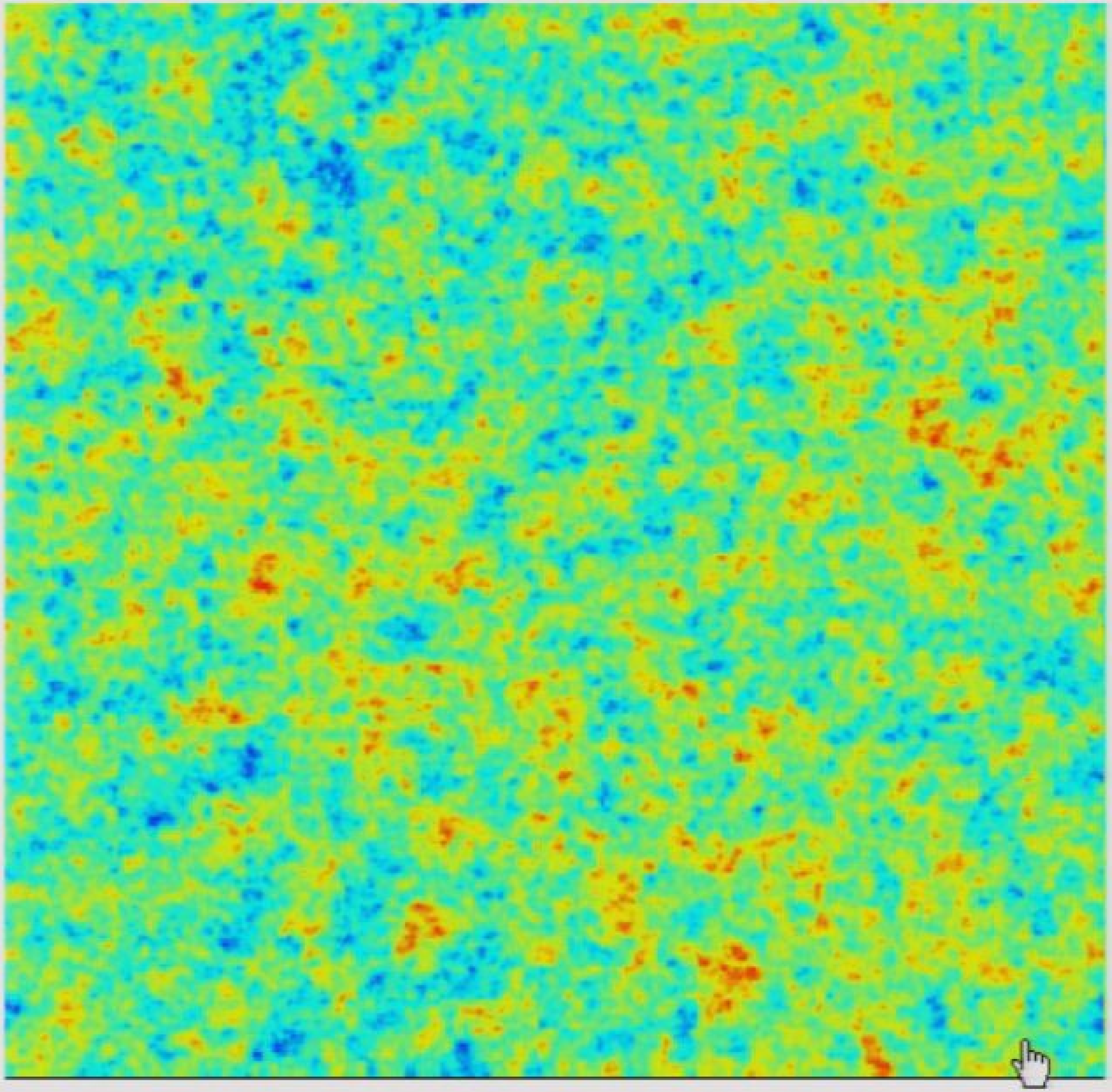
CMB temperature



CMB temperature



CMB temperature



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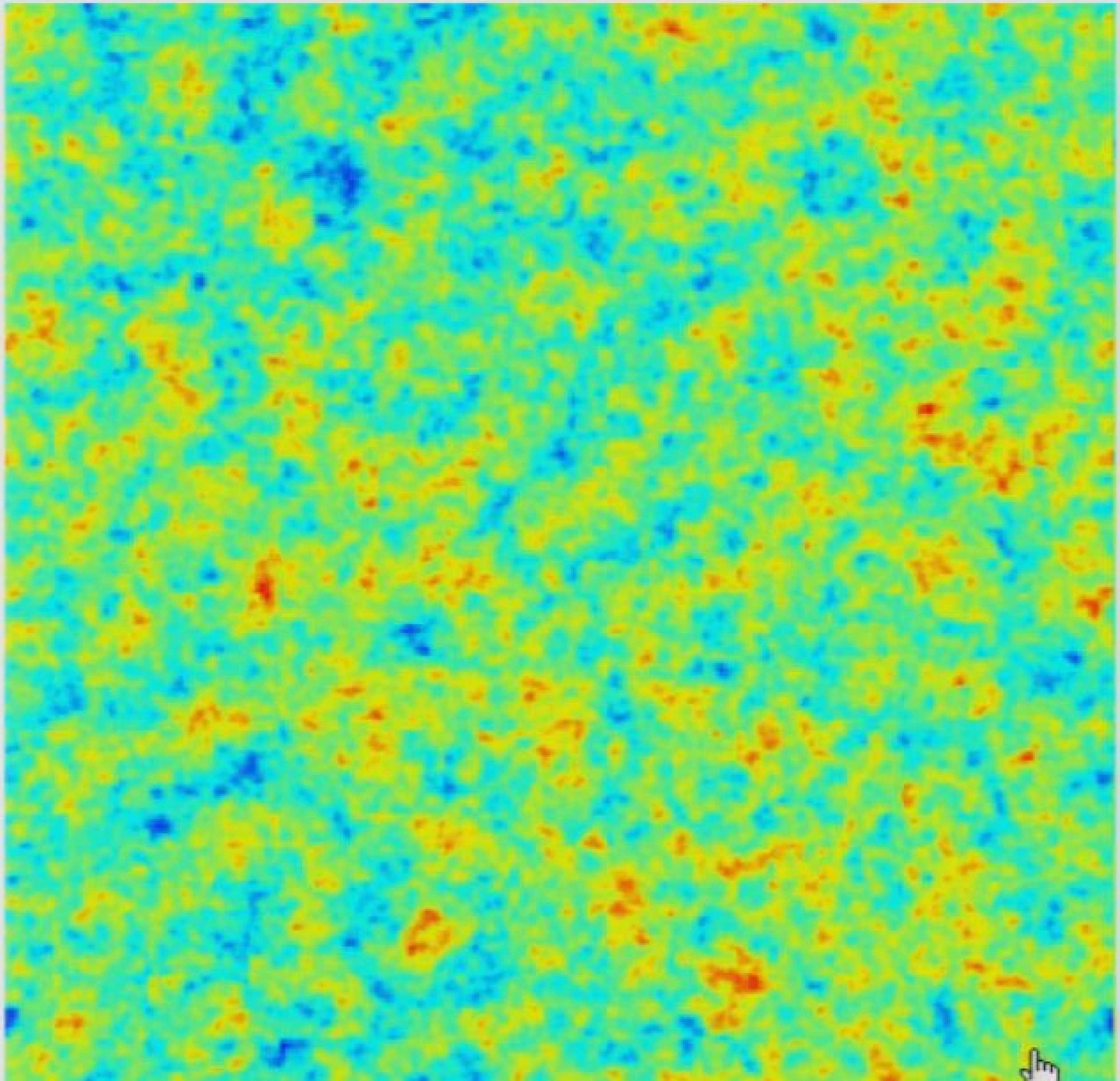

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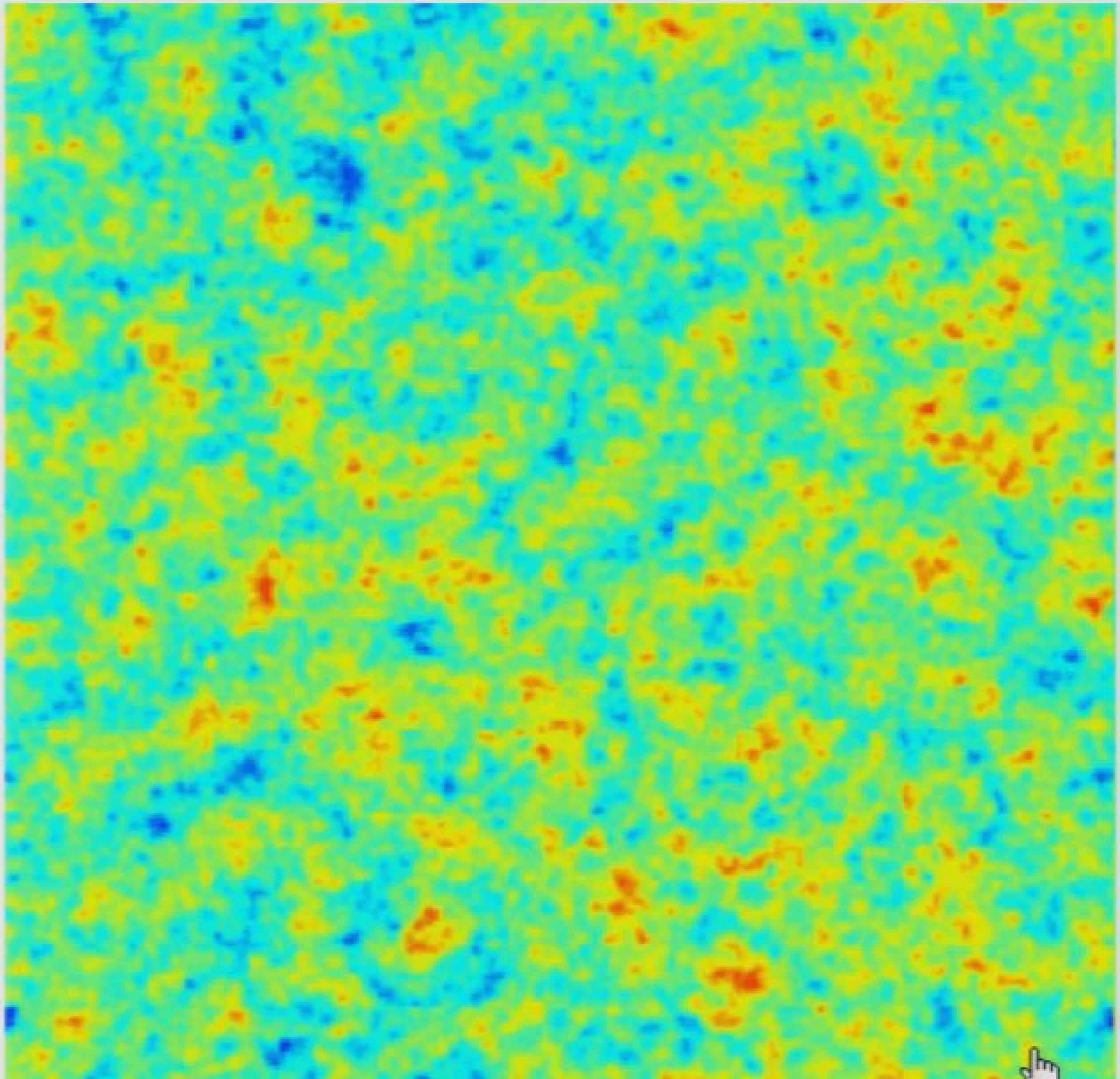
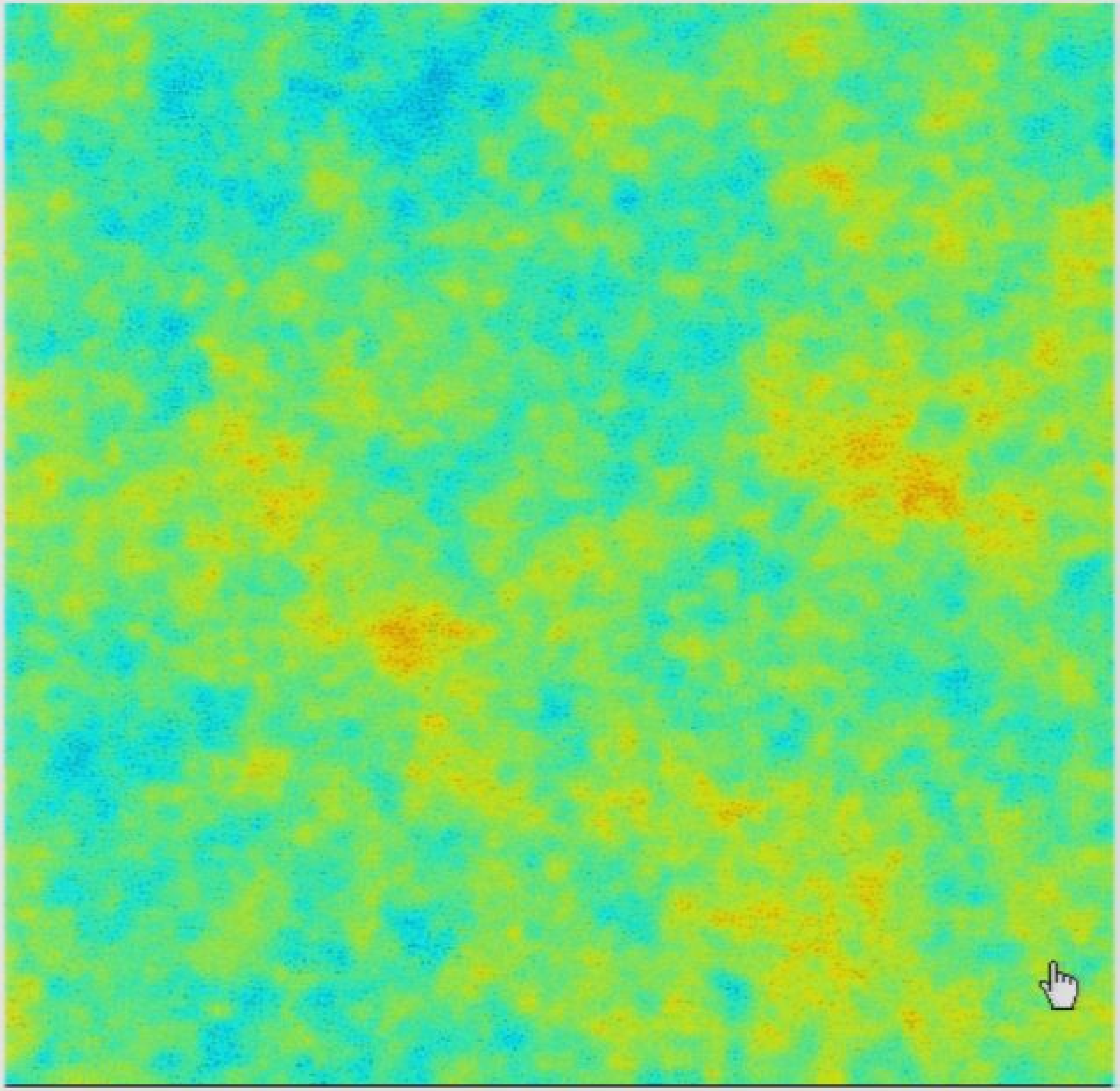


CMB temperature



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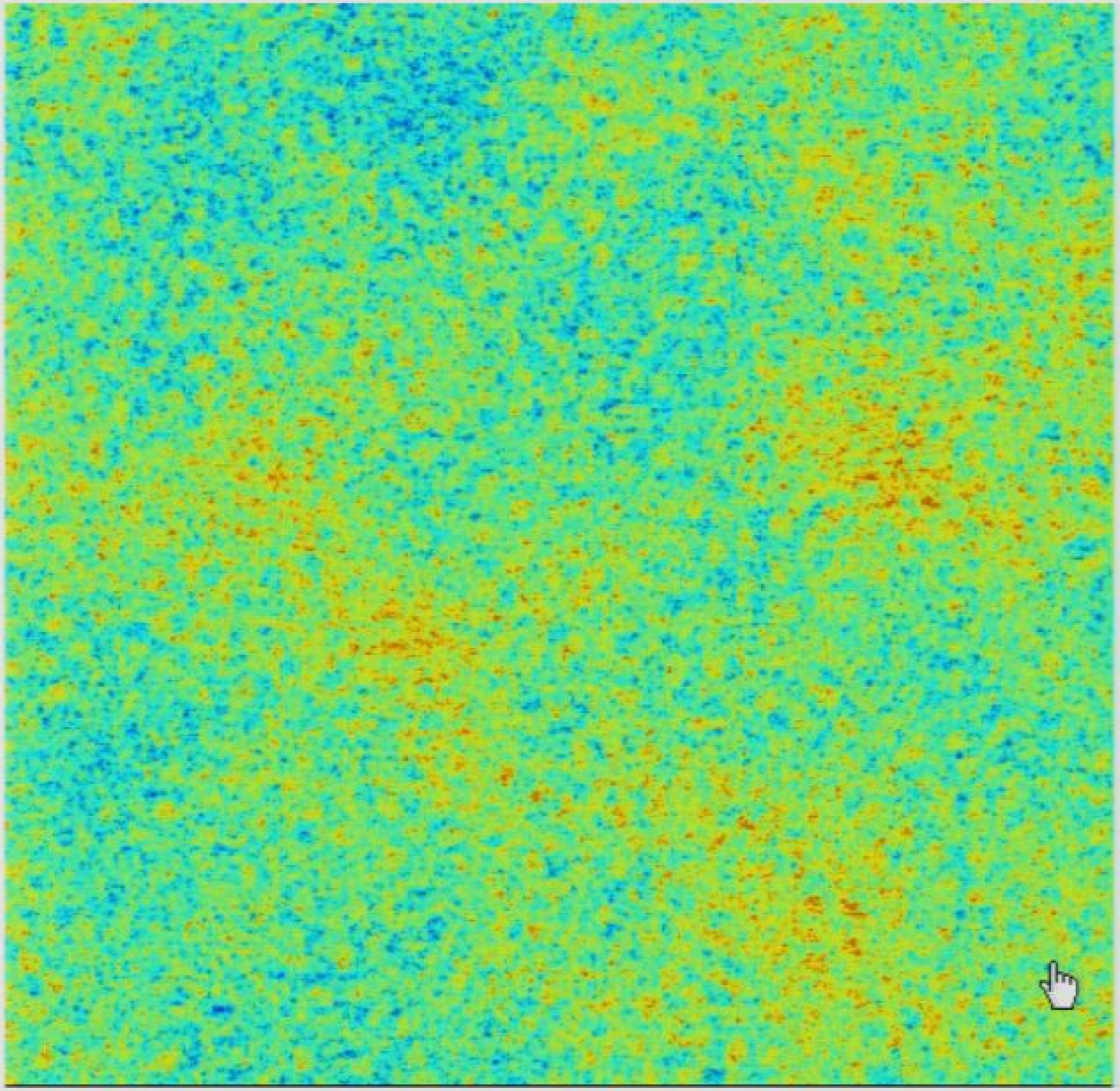

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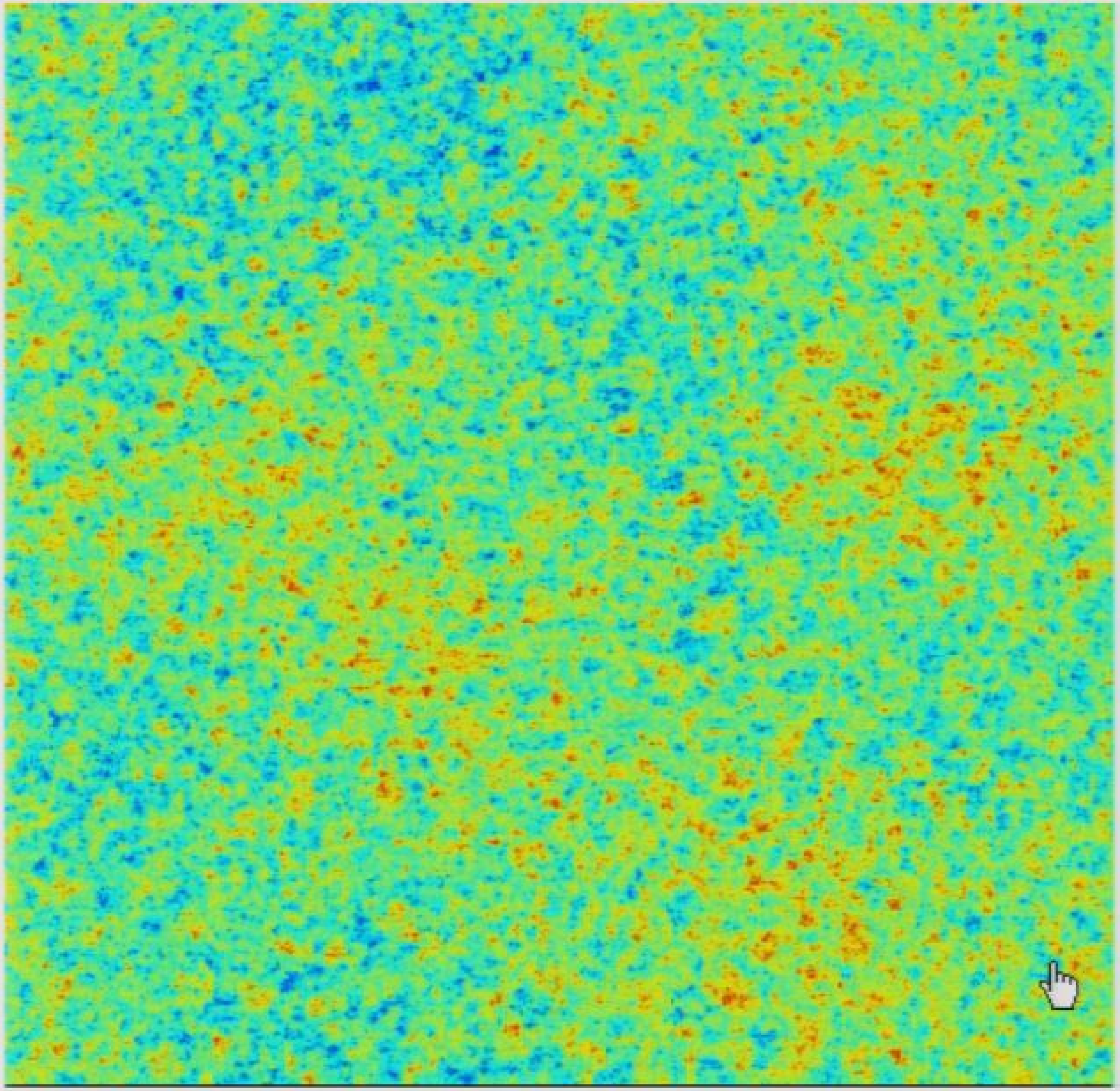

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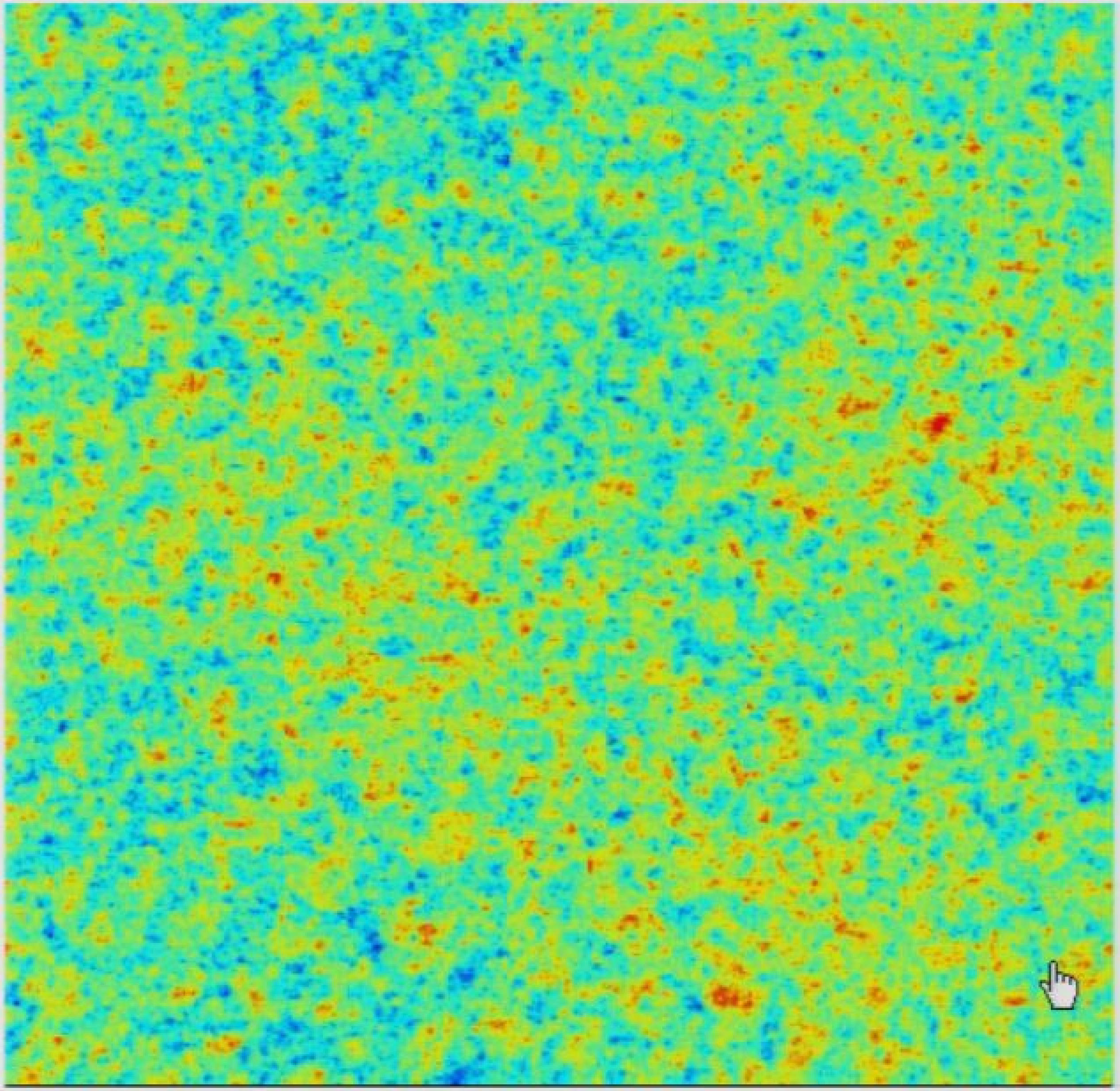

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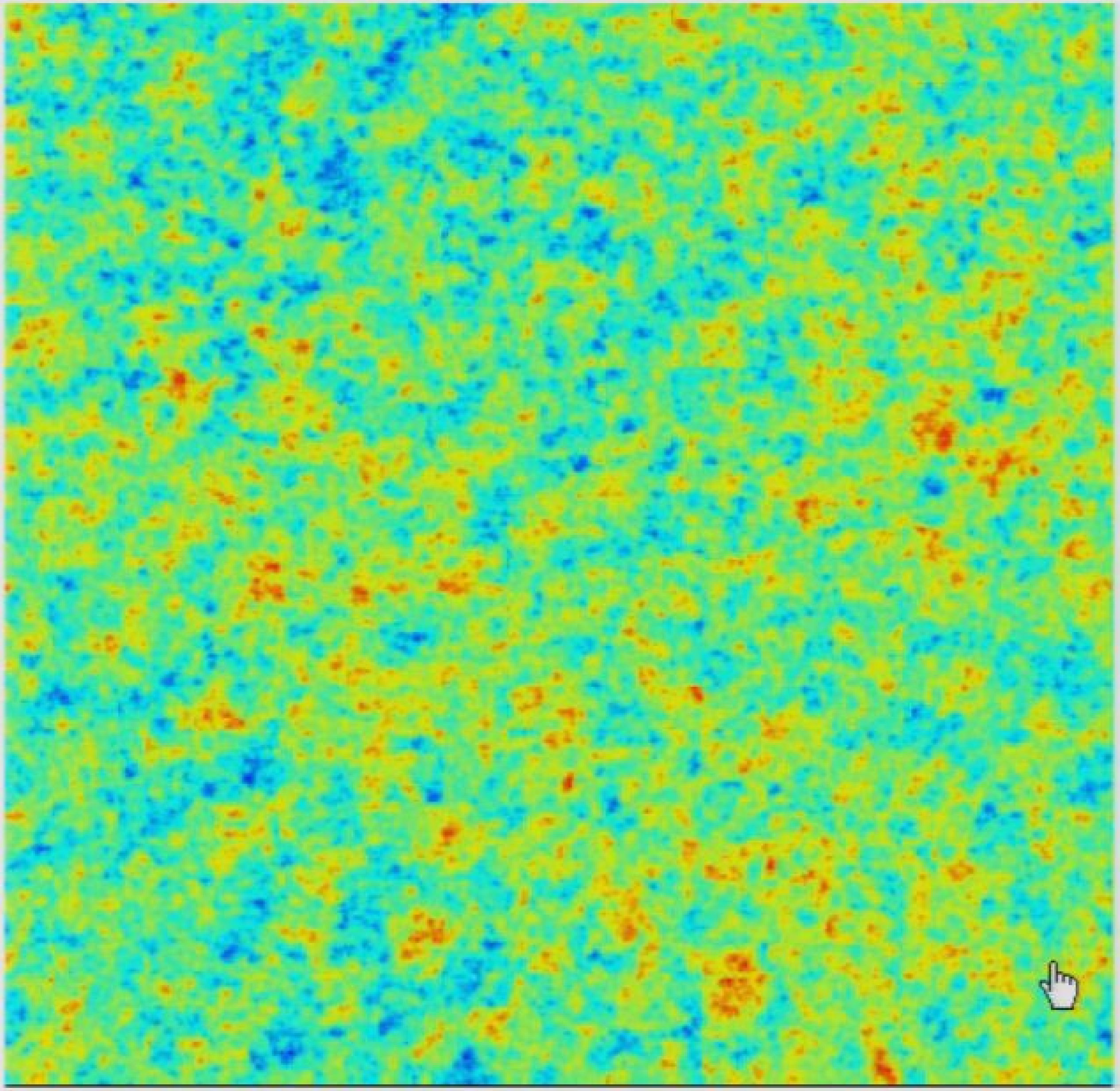

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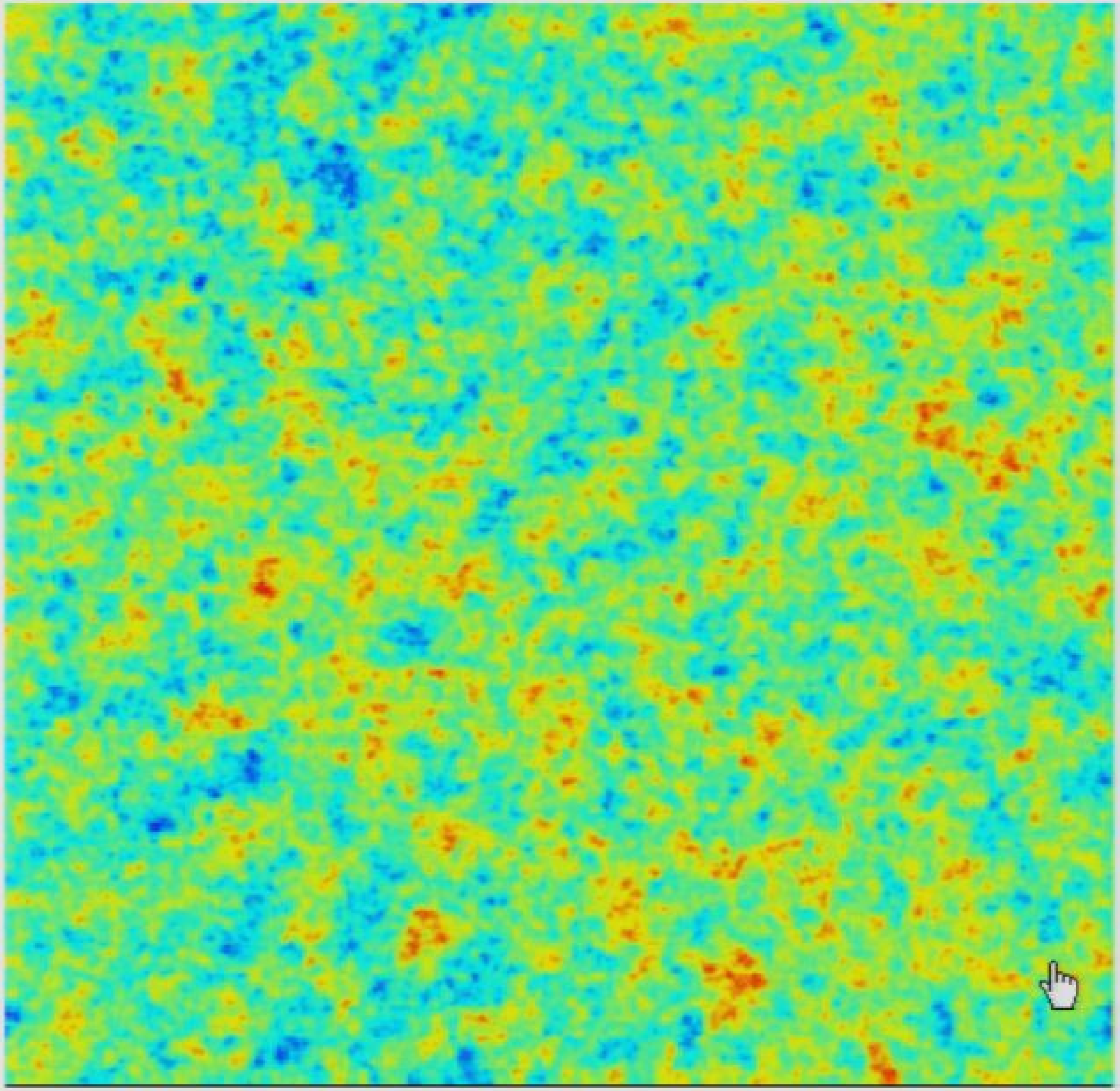

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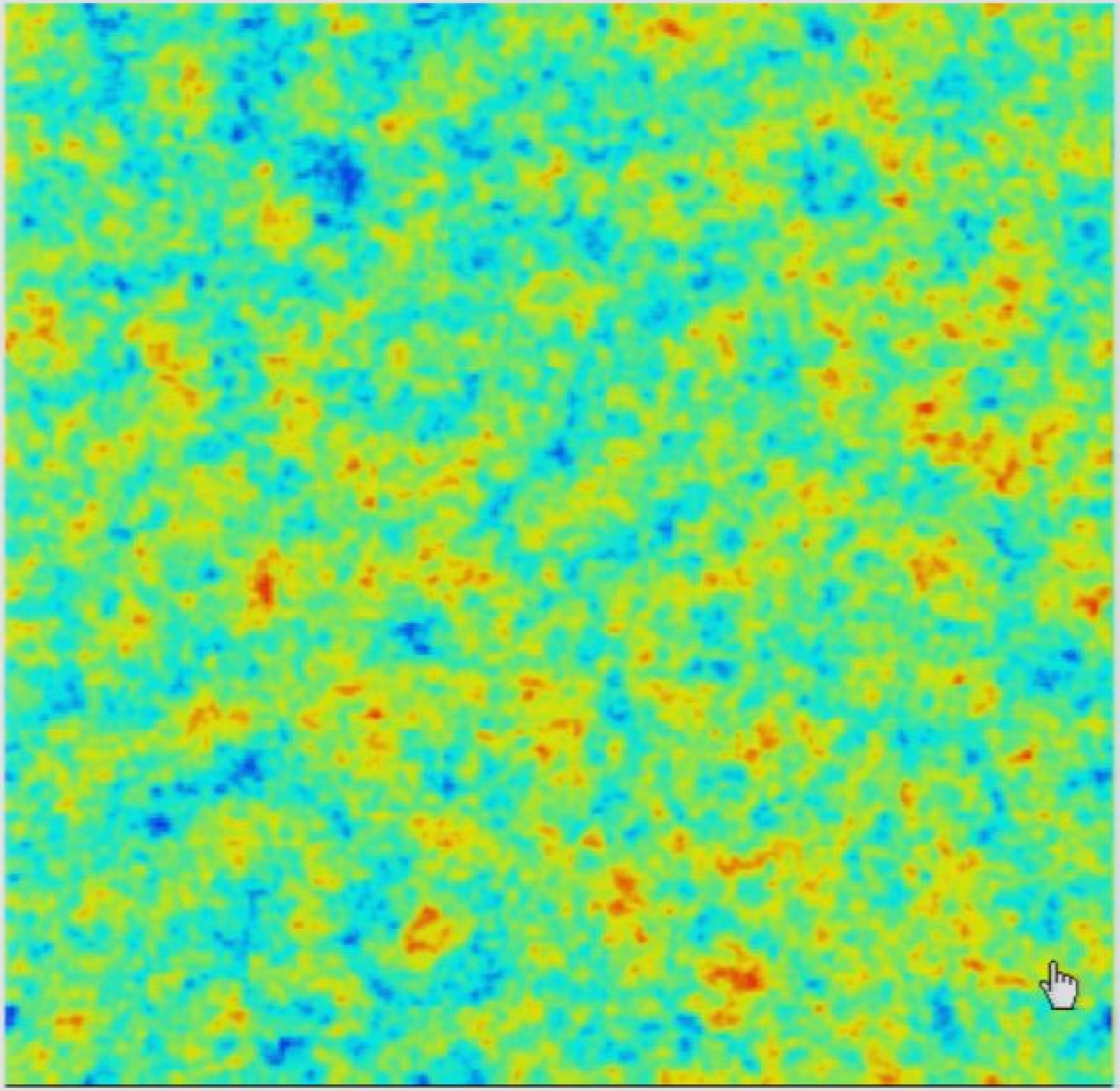
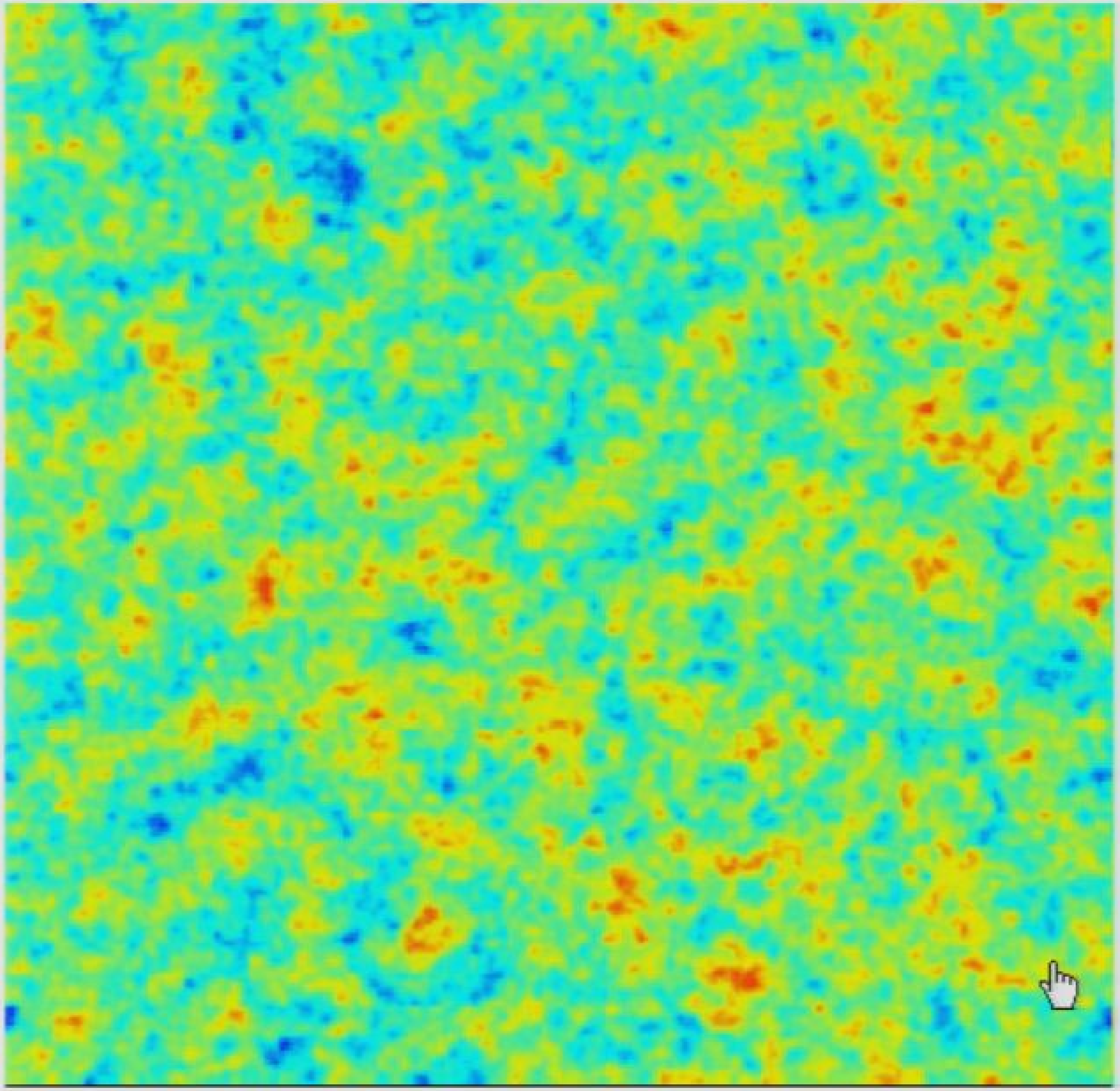


CMB temperature



Why the CMB temperature (and polarization) is great

- Probes scalar, vector and tensor mode perturbations

- The earliest possible observation
  (bar future neutrino anisotropy surveys etc…)

- Includes super-horizon scales, probing the largest observable perturbations

- Observable now

Why it is bad

- Only one sky, so cosmic variance limited on large scales

- Diffusion damping and line-of-sight averaging:
  all information on small scales destroyed! ($l>\sim 2500$)

- Only a 2D surface (+reionization), no 3D information

If only we could observe the CDM perturbations...

- not erased by diffusion damping (if cold): power on all scales
- full 3D distribution of perturbations

What about the baryons?

- fall into CDM potential wells; also power on small scales
- full 3D distribution
- but baryon pressure non-zero: very small scales still erased

How does the information content compare with the CMB?

CMB temperature, $1<l<\sim 2000$:

- about 10^6 modes
- can measure P_k to about 0.1% at $l=2000$ (k Mpc~ 0.1)

Dark age baryons at one redshift, $1 < l < 10^6$:

- about 10^{12} modes
- measure P_k to about 0.0001% at $l=10^6$ (k Mpc ~ 100)

What about different redshifts?

About 10^4 independent redshift shells at $l=10^6$

- total of 10^{16} modes
- measure P_k to an error of 10^{-8} at 0.05 Mpc scales

e.g. running of spectral index:

If $n_s = 0.96$ maybe expect running $\sim (1-n_s)^2 \sim 10^{-3}$

Expected change in $P_k \sim 10^{-3}$ per log k

- measure running to 5 significant figures!?

So worth thinking about… can we observe the baryons somehow?

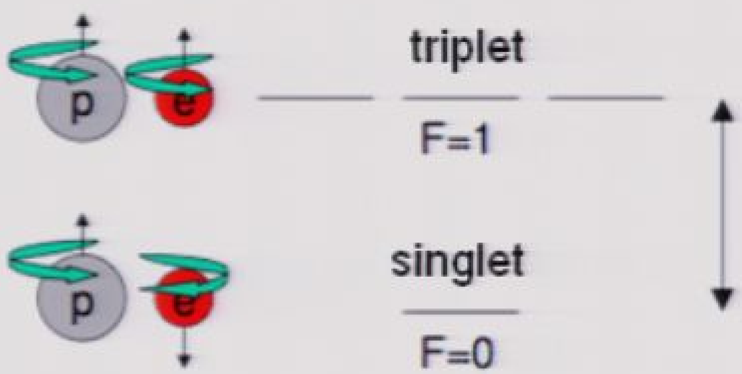
- How can light interact with the baryons (mostly neutral H + He)?

- after recombination, Hydrogen atoms in ground state and CMB photons have hν << Lyman-alpha frequency

  * high-frequency tail of CMB spectrum exponentially suppressed
  * essentially no Lyman-alpha interactions
  * atoms in ground state: no higher level transitions either

- Need transition at much lower energy

* Essentially only candidate for hydrogen is the hyperfine spin-flip transition



$$\Delta E = \frac{4}{3}\alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9\,\mu\text{eV} = h(1420\text{MHz})$$

$$\lambda = 21\,\text{cm}$$

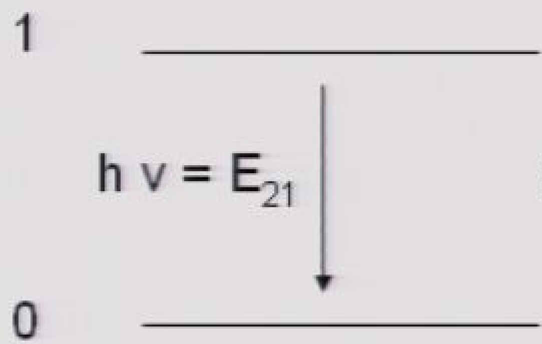
Credit: Sigurdson

Define spin temperature T_s

$$n_1/n_0 = 3e^{-T_\star/T_s} \text{ where } T_\star \equiv h_p \nu_{21}/k_B \approx 0.068\text{K}$$

What can we observe?

Spontaneous emission: $n_1 A_{10}$ photons per unit volume per unit proper time



Rate: $A_{10} = 2.869 \times 10^{-15}$ /s

Stimulated emission: net photons $(n_1 B_{10} - n_0 B_{01}) I_\nu$

Total net number of photons:

$$\mathrm{d}n_{21} = [(n_1 - 3n_0)B_{10}I_\nu + A_{10}n_1]\,\delta(E - E_{21})\mathrm{d}\tau\mathrm{d}E.$$

In terms of spin temperature: $\propto \frac{T_s - T_\gamma}{T_s}$

Net emission or absorption if levels not in equilibrium with photon distribution

- observe baryons in 21cm emission or absorption if $T_s <> T_{CMB}$

What determines the spin temperature?

- Interaction with CMB photons: drives T_s towards T_{CMB}
- Collisions between atoms: drives T_s towards gas temperature T_g

$T_{CMB} = 2.726\text{K}/a$

$$\dot{\bar{T}}_g + 2\mathcal{H}\bar{T}_g = -\frac{8 a \sigma_T \bar{\rho}_\gamma x_e}{3 m_e c (1 + f_{\rm He} + x_e)} (\bar{T}_g - \bar{T}_\gamma)$$

At recombination, Compton scattering makes $T_g = T_{CMB}$

Later, once few free electrons, gas cools: $T_g \sim mv^2/k_B \sim 1/a^2$

→ Spin temperature driven below T_{CMB} by collisions:
- atoms have net absorption of 21cm CMB photons

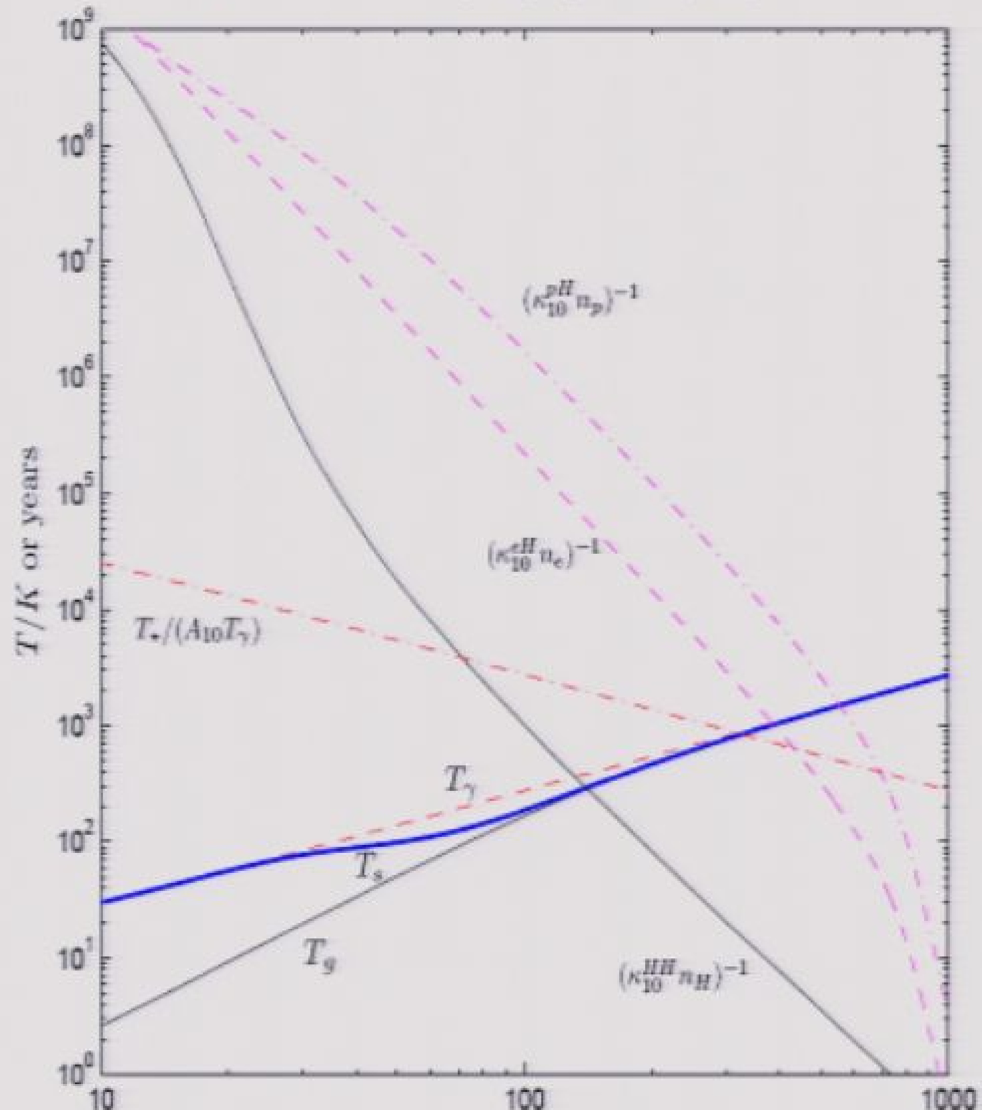
- (+Interaction with Lyman-alpha photons - not important during dark ages)

$$\frac{\partial N_0}{\partial \tau} = -N_0(C_{01} + B_{01} I_{\nu 0}) + N_1(C_{10} + A_{10} + B_{10} I_{\nu 0})$$

C: collisions
A: spontaneous
B: stimulated

$$\Rightarrow \quad T_s = T_\gamma \left(\frac{C_{10}/T_\gamma + A_{10}/T_\star}{C_{10}/T_g + A_{10}/T_\star} \right)$$

$[H^{-1} >> C_{10}^{-1}]$



Subtleties: is $T_s(x,t)$ a good representation?

- Collision rate depends on atomic velocity: really need to do full distribution function with $T_s(x,t,v)$ – few % effect
  Hirata & Sigurdson astro-ph/0605071

- T_s representation assumes triplet state isotropic:

  - anisotropies in photon distribution will drive anisotropic distribution

  - but collisions isotropize

  - parity invariance implies only even photon moments important

  - dipole has no effect, other anisotropies ~ 10^{-4}: OK

What's the power spectrum?

Use Boltzmann equation for change in CMB due to 21cm absorption:

Background: $\bar{\rho}_s \equiv \frac{1}{4\pi E_{21}^2}\frac{3\bar{n}_H A_{10}}{4}\left(\frac{\bar{T}_s-\bar{T}_\gamma}{\bar{T}_s}\right)$

Perturbation: $\Delta_s \equiv \Delta_H + \frac{\bar{T}_\gamma}{\bar{T}_s-\bar{T}_\gamma}\left(\Delta_{T_s}-\Delta_{T_\gamma}\right)$

$$\left.\frac{\mathrm{d}f}{\mathrm{d}\lambda}\right|_H = E_{21}\bar{\rho}_s\left[1+\Delta_s-\frac{\bar{T}_\gamma}{\bar{T}_s-\bar{T}_\gamma}\{\mathbf{e}\cdot(\mathbf{v}_\gamma-\mathbf{v})+\Theta_+\}\right]\delta(\epsilon(1-\mathbf{e}\cdot\mathbf{v})/a-E_{21})$$

Fluctuation in density of H atoms,
+ fluctuations in spin temperature

l >1 anisotropies in T_{CMB}

Doppler shift
to gas rest frame

CMB dipole seen by H atoms:
more absorption in direction of gas motion relative to CMB

+ reionization re-scattering terms

Solve Boltzmann equation in Newtonian gauge:

Main monopole source

Effect of local CMB anisotropy

Redshift distortions

$$\delta f(\eta_A, \mathbf{x}_A, \epsilon, \hat{\mathbf{n}}) =$$

$$e^{-\tau_\epsilon} \bar{f}(\epsilon) \left[\Delta_s + \psi + \hat{\mathbf{n}} \cdot \mathbf{v} + \frac{\bar{T}_\gamma}{\bar{T}_s - \bar{T}_\gamma} \{ \hat{\mathbf{n}} \cdot (\mathbf{v}_\gamma - \mathbf{v}) - \Theta_+ \} + \frac{1}{\mathcal{H}} \left(-\frac{\mathrm{d}\psi}{\mathrm{d}\eta} + (\dot{\phi} + \dot{\psi}) + \hat{\mathbf{n}} \cdot \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}\eta} \right) \right]_\epsilon$$

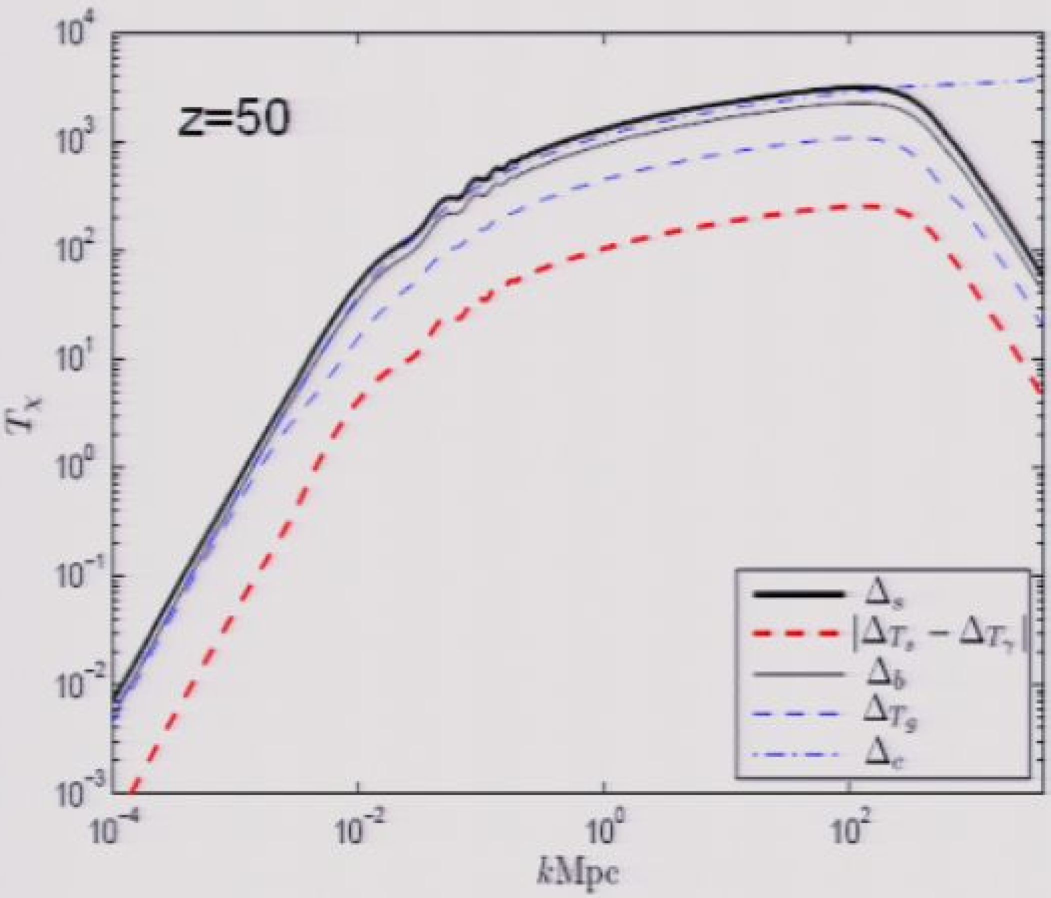
$$+ e^{-\tau_\epsilon} \bar{f}_{,\ln \epsilon}(\epsilon) \left(e^{\tau_\epsilon} \psi_A - \psi_\epsilon + \hat{\mathbf{n}} \cdot \mathbf{v}_\epsilon \right) - \bar{f}_{,\ln \epsilon}(\epsilon) \int_{\eta_\epsilon}^{\eta_A} \mathrm{d}\eta e^{-\tau} (\dot{\phi} + \dot{\psi}) - \int_{\eta_\epsilon}^{\eta_A} \mathrm{d}\eta \dot{\tau} e^{-\tau} \left(\delta f_0 + \bar{f}_{,\ln \epsilon}(\epsilon)(\hat{\mathbf{n}} \cdot \mathbf{v} - \psi) + \frac{f_2}{10} \right)$$

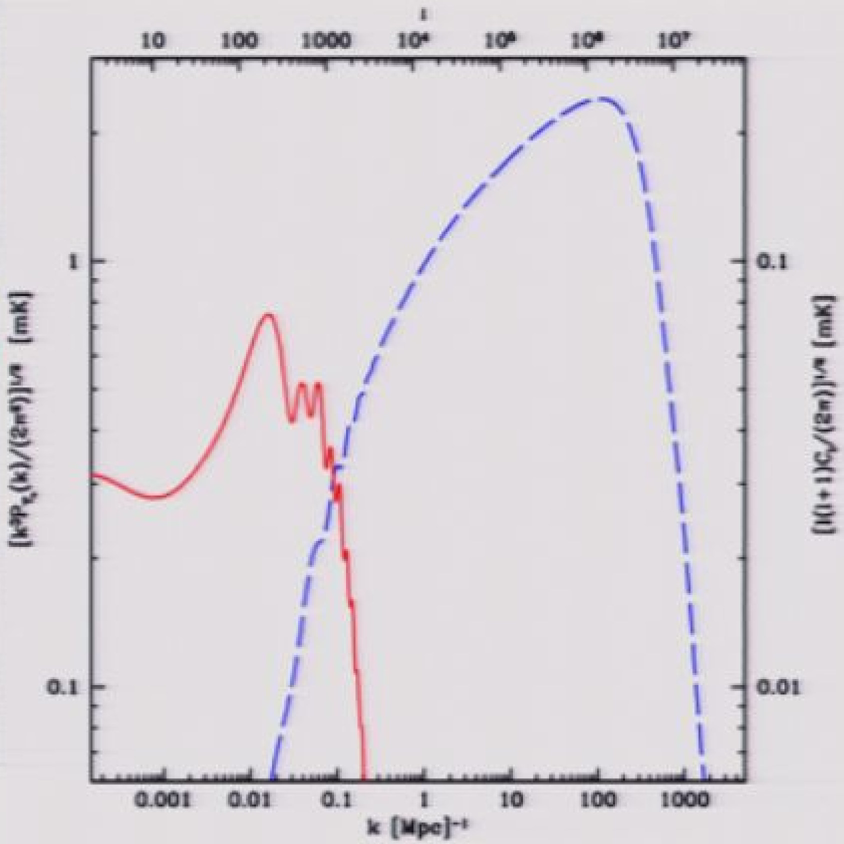
Sachs-Wolfe, Doppler and ISW change to redshift

Tiny Reionization sources

For k >> aH good approximation is $\delta f(\eta_A, \mathbf{x}_A, \epsilon, \hat{\mathbf{n}}) \approx e^{-\tau_\epsilon} \bar{f}(\epsilon) \left[\Delta_s - \frac{1}{\mathcal{H}} \hat{\mathbf{n}} \cdot \frac{\partial \mathbf{v}}{\partial \chi} \right]_\epsilon$

21cm does indeed track baryons when $T_s < T_{CMB}$





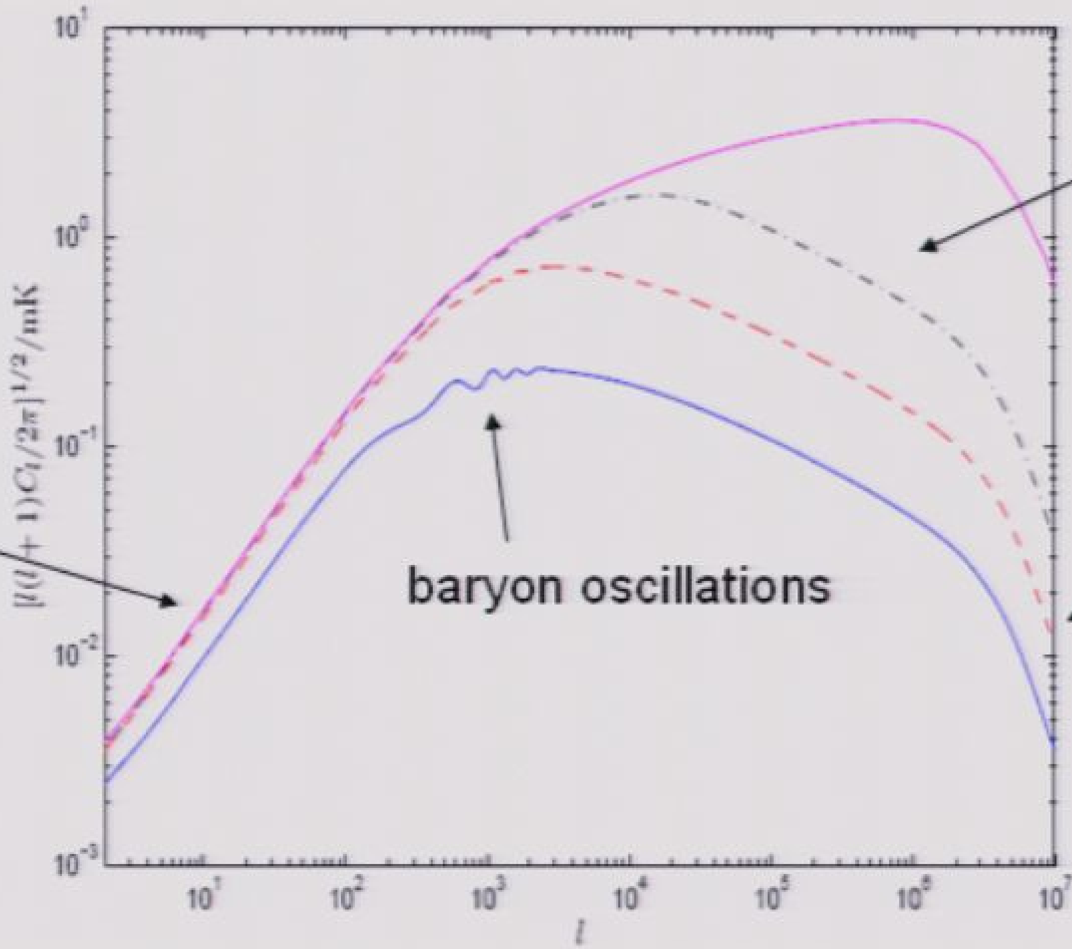
Kleban et al. hep-th/0703215

So can indirectly observe baryon power spectrum at 30< z < 100-1000 via 21cm

Observable angular power spectrum: $C_l(z,z') = 4\pi \int \mathrm{d}\ln k\, \mathcal{P}_\chi(k) F_l(k,z) F_l(k,z'),$

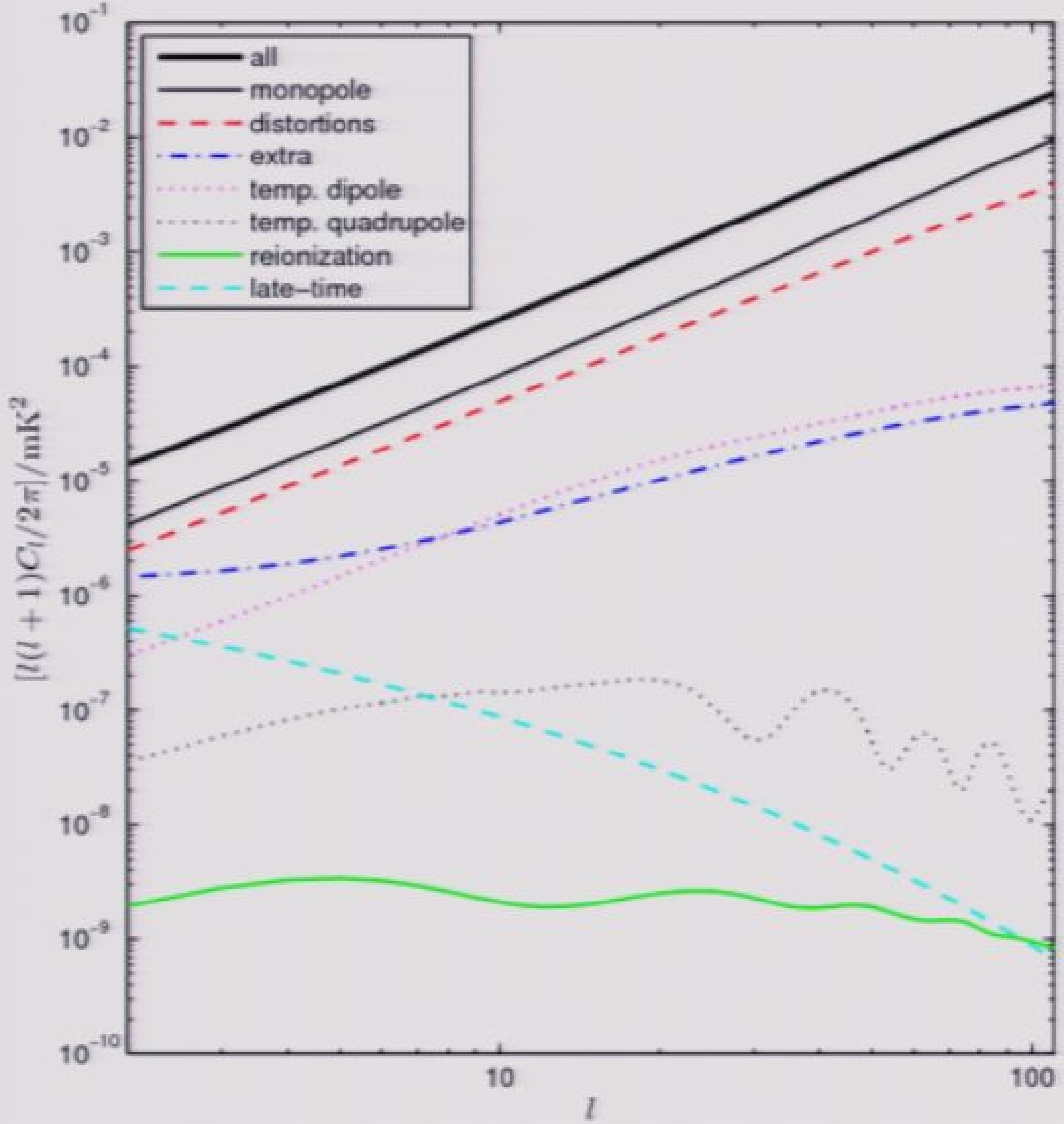
Integrate over window in frequency

Small scales: $F_l(\eta_A, \mathrm{x}_A, \epsilon, k) \approx e^{-\tau_\epsilon} \bar{f}(\epsilon) \left[\Delta_* j_l(k\chi_\epsilon) + \frac{kv}{\mathcal{H}} j_l''(k\chi_\epsilon) \right]$



z=50 $\Delta\nu = \{1, 0.1, 0.01, 0\}\mathrm{MHz}$

What about large scales (Ha >~ k)?



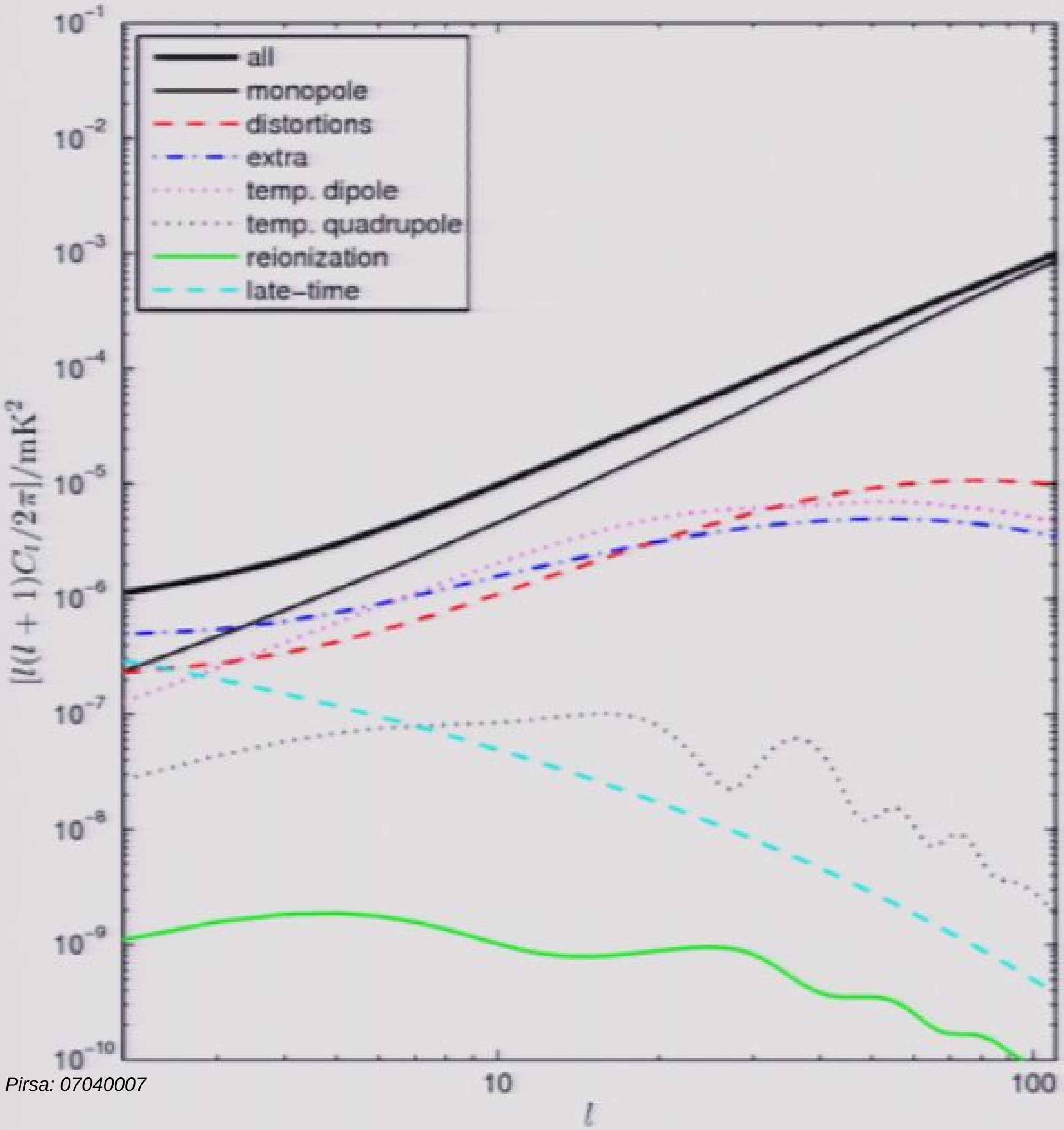
Narrow redshift window

$z = 50$ with $\Delta\nu = 0.01\mathrm{MHz}$

<~ 1% effect at l<50

Extra terms largely negligible

Average over lots of redshift shells?



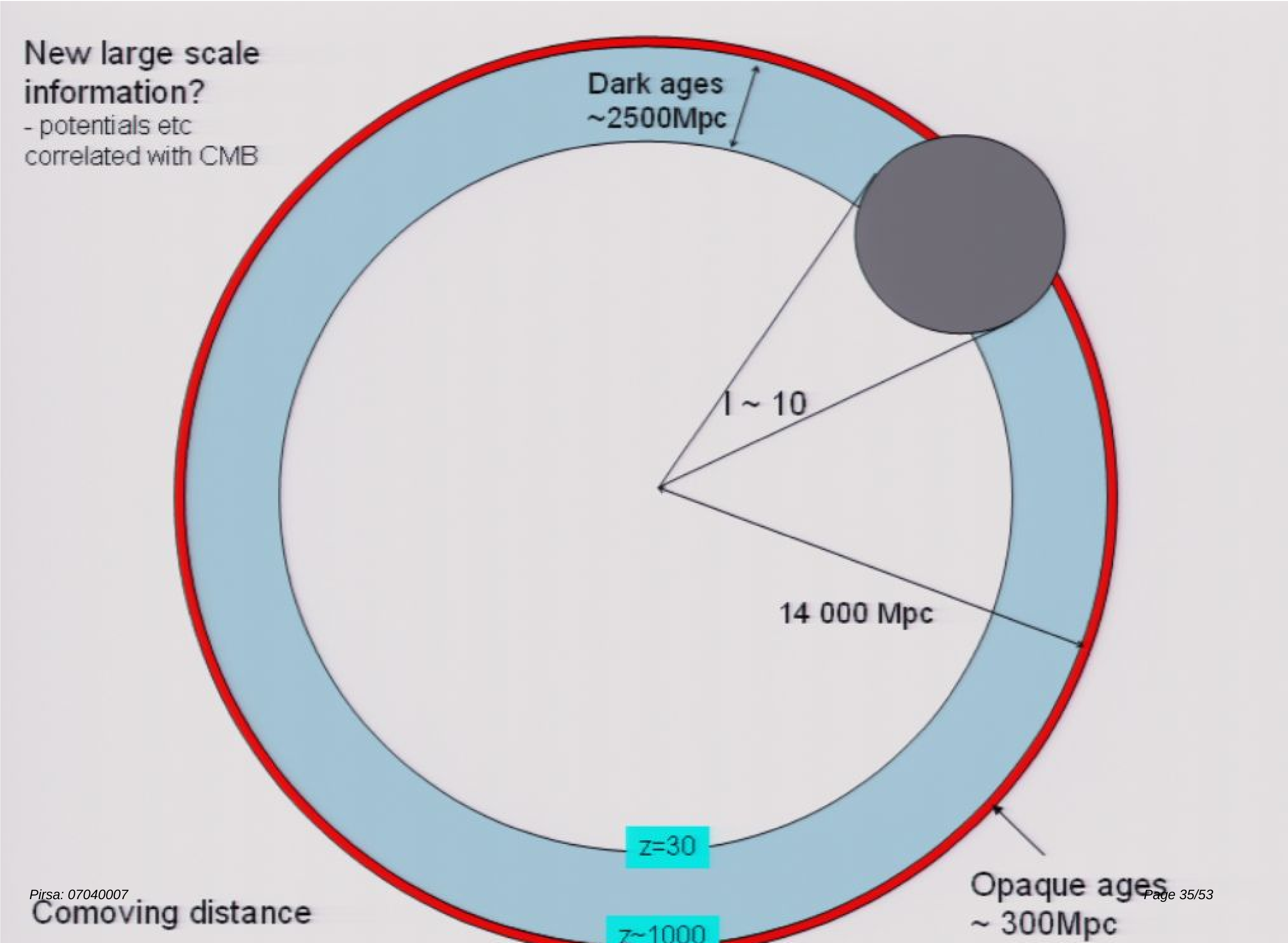
Average over many redshifts to reduce large scale noise

e.g. window 33<z<47

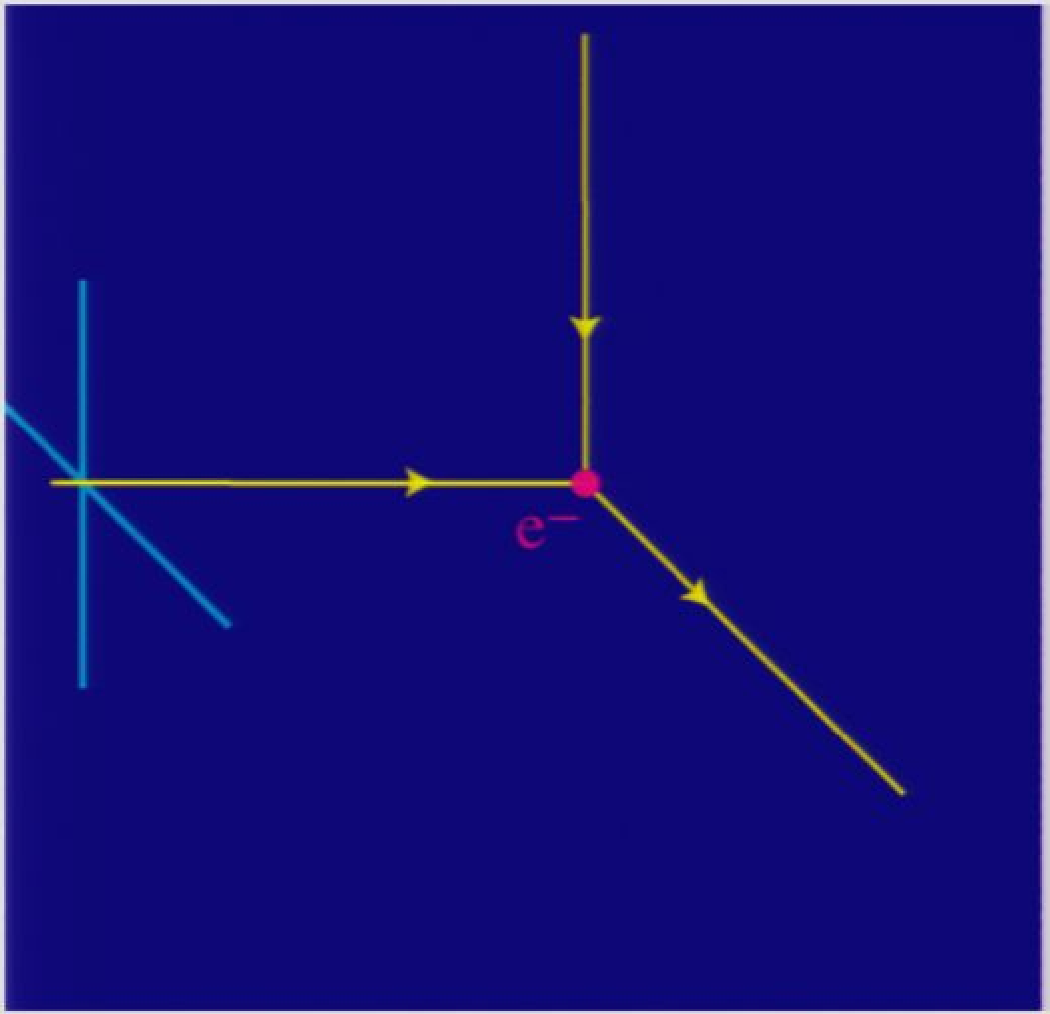
Redshift distortions suppressed

Extra terms
give >1% effect at l<100

BUT: e.g. ISW still hidden


New large scale information?
- potentials etc correlated with CMB
Dark ages ~2500Mpc
l ~ 10
14 000 Mpc
z=30
z~1000
Opaque ages ~ 300Mpc
Comoving distance

Polarization from Thomson Scattering?



W Hu

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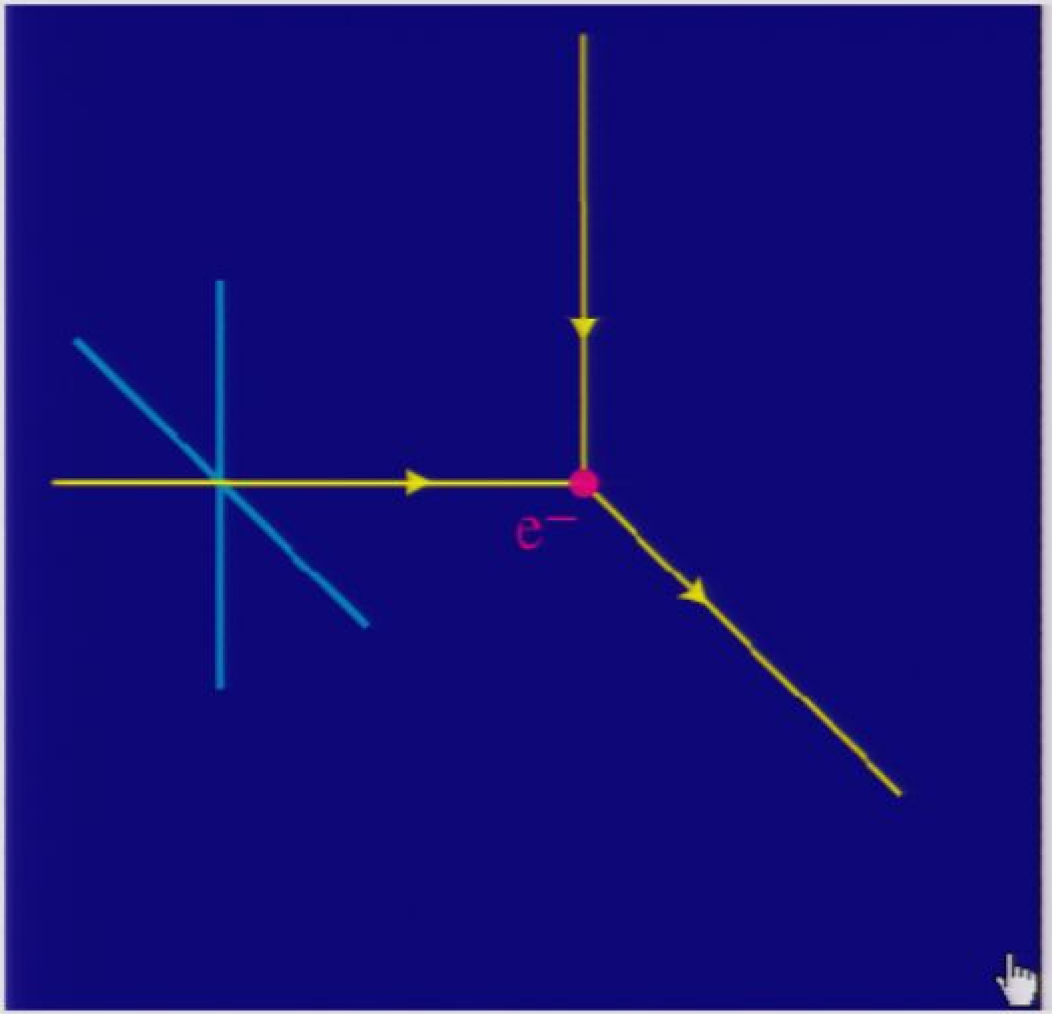

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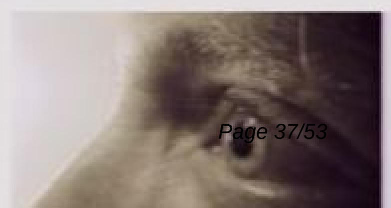

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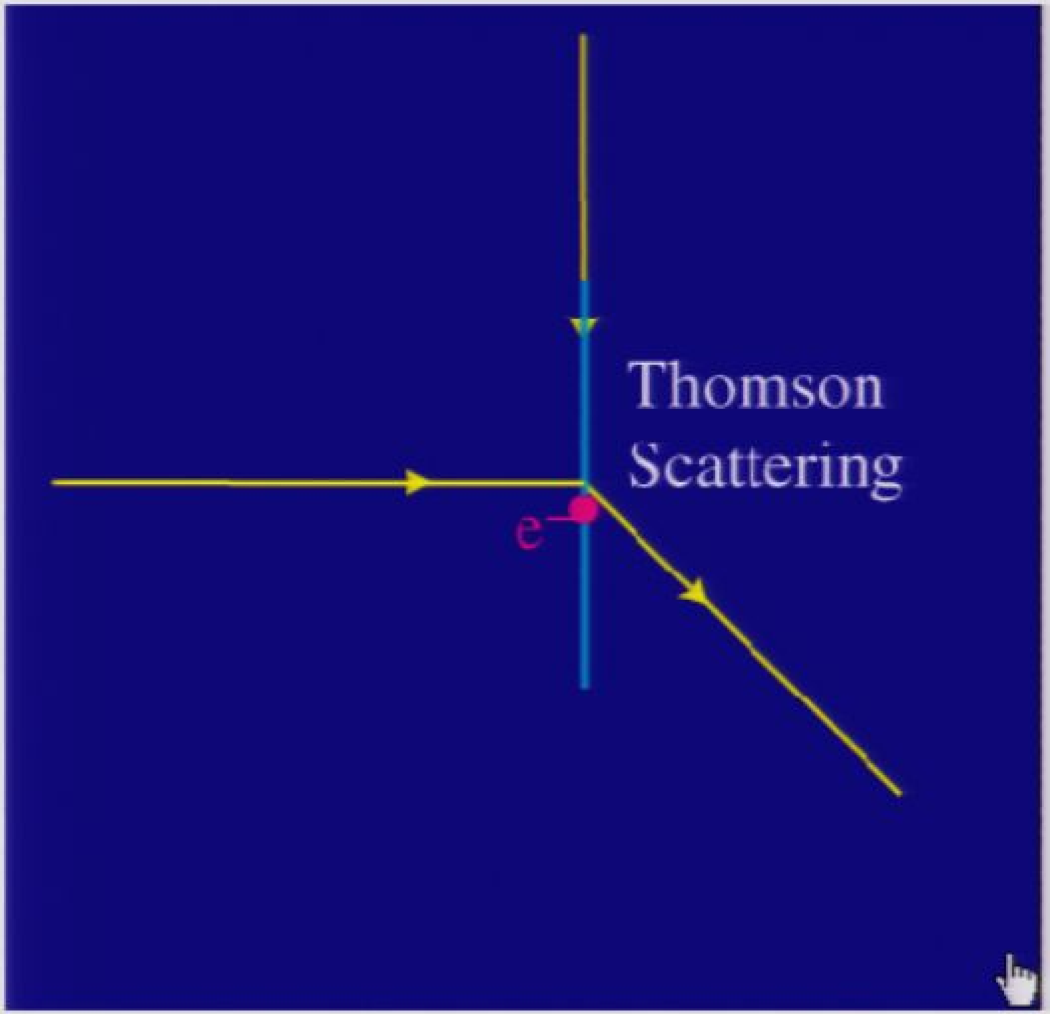

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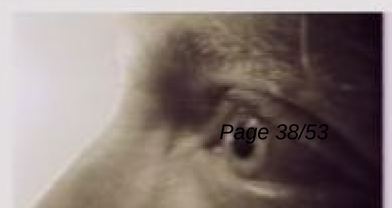

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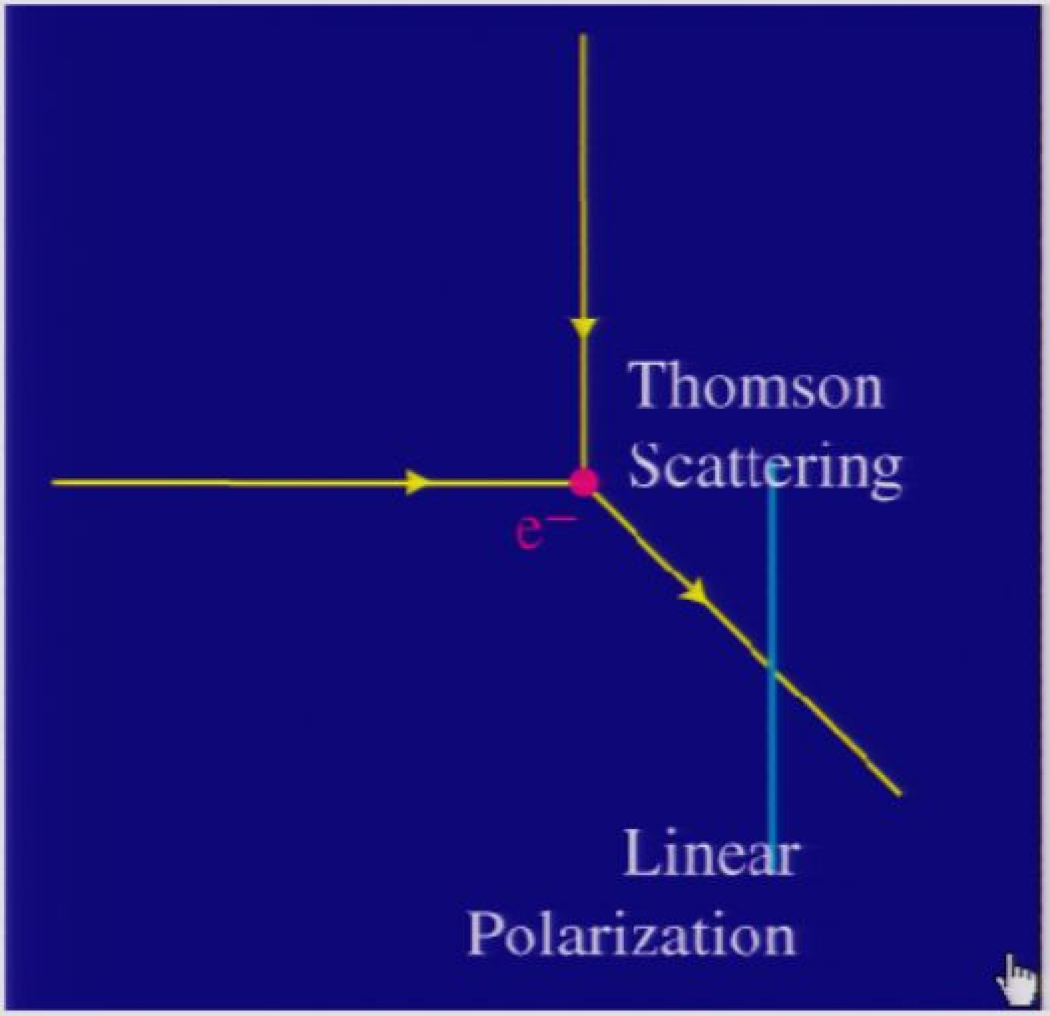

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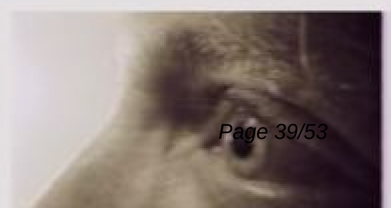
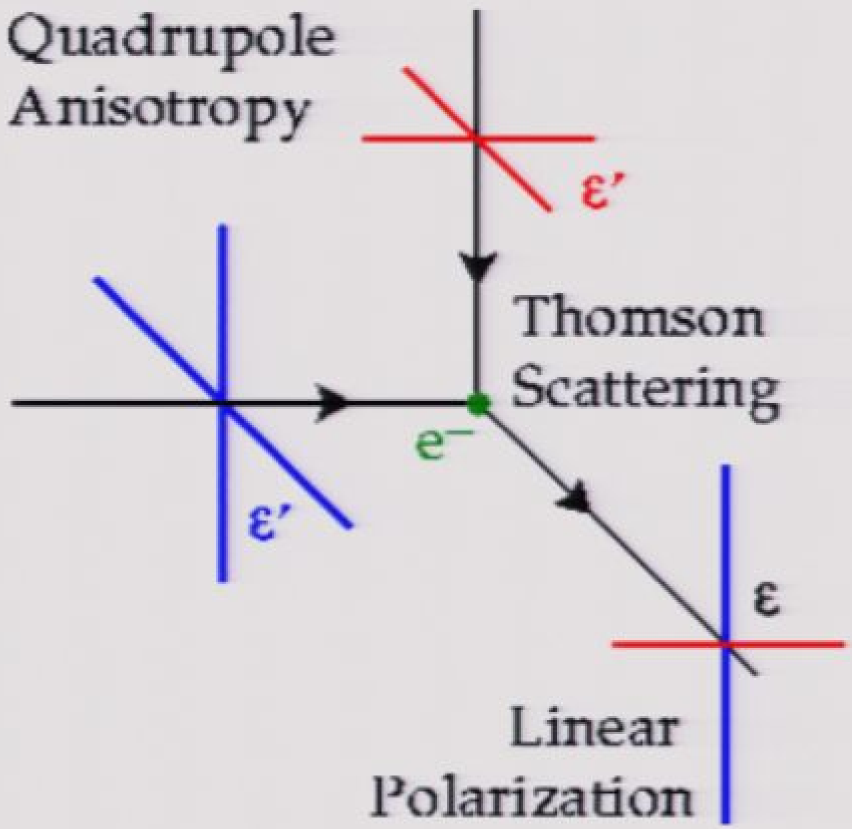


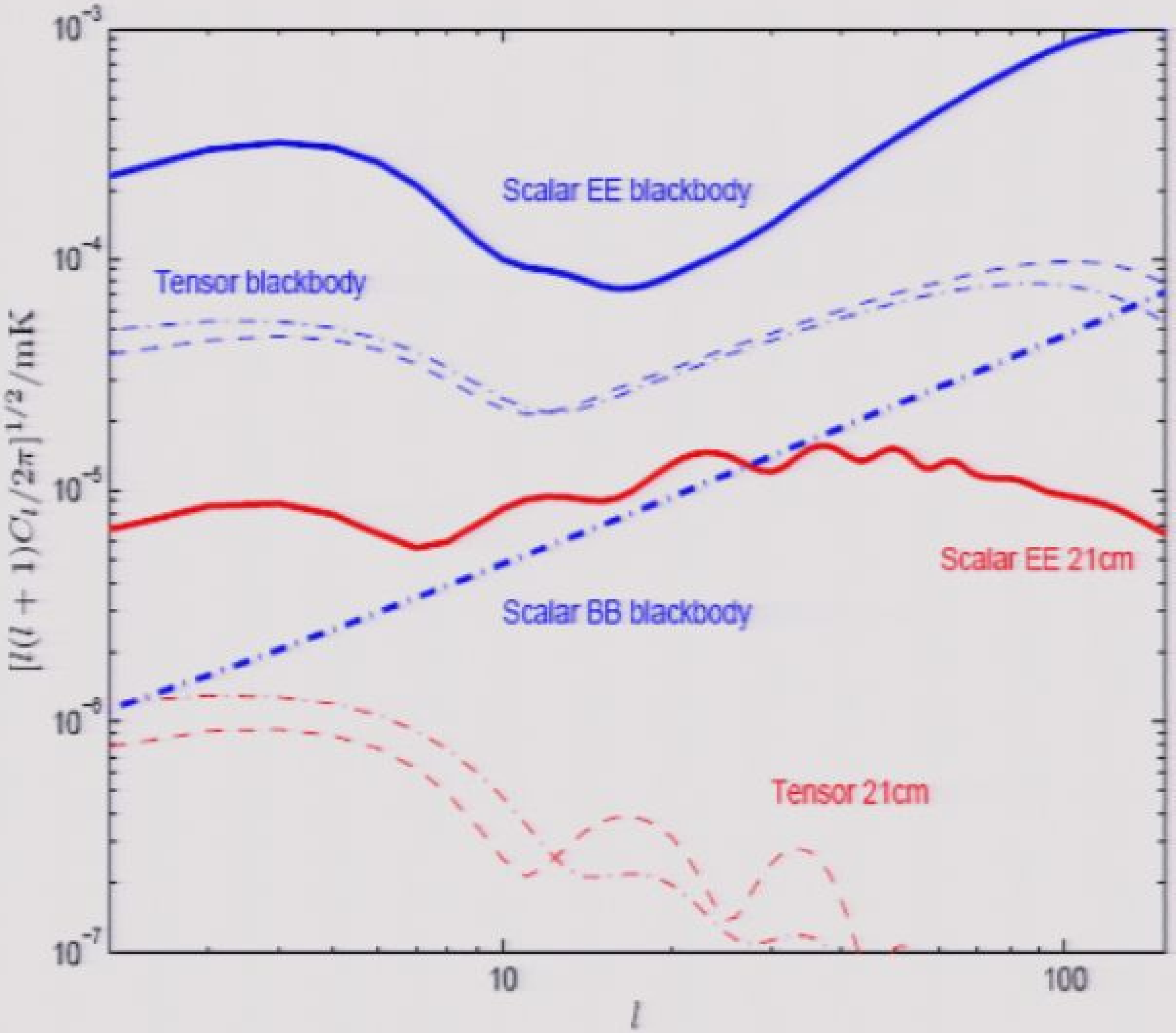
Generated during reionization by Thomson scattering of anisotropic photon distribution



Hu astro-ph/9706147

- re-scattering of scalar modes at reionization
- gravitational waves between 21cm absorption and reionization
- temperature anisotropy at source due to gravitational waves between source and last scattering

Rather small!



z=50, r=0.1 tensors

c.f. Babich: astro-ph/0505358

Improved modelling of (very) small-scale perturbations

- Small scale CDM and baryon power spectrum sensitive to baryon pressure:

$$\frac{\partial^2 \Delta_b}{\partial \eta^2} + \mathcal{H}\frac{\partial \Delta_b}{\partial \eta} + k^2 c_s^2 \Delta_b = 4\pi G a^2 \sum_i (\delta\rho_i + 3\delta p_i)$$

$c_s^2 = \delta p / \delta \rho$ Perfect gas (PV=nRT): $c_s^2 \Delta_g = \frac{k_B \bar{T}_g}{\mu}\left(\Delta_g + \Delta_{T_g}\right)$

- Sound speed depends on temperature perturbation Δ_{T_g}
  - perturbed Compton cooling equation:

$$\dot{\Delta}_{T_g} = 2\dot{\phi} - \frac{2}{3}kv - \frac{8a\sigma_T \bar{\rho}_\gamma x_e}{3m_e c(1 + f_{\rm He} + x_e)}\left[\left(1 - \frac{\bar{T}_\gamma}{\bar{T}_g}\right)\left\{4\Delta_{T_\gamma} + \psi + \frac{\Delta_{x_e}}{1 + x_e/(1 + f_{\rm He})}\right\} + \frac{\bar{T}_\gamma}{\bar{T}_g}\left(\Delta_{T_g} - \Delta_{T_\gamma}\right)\right]$$

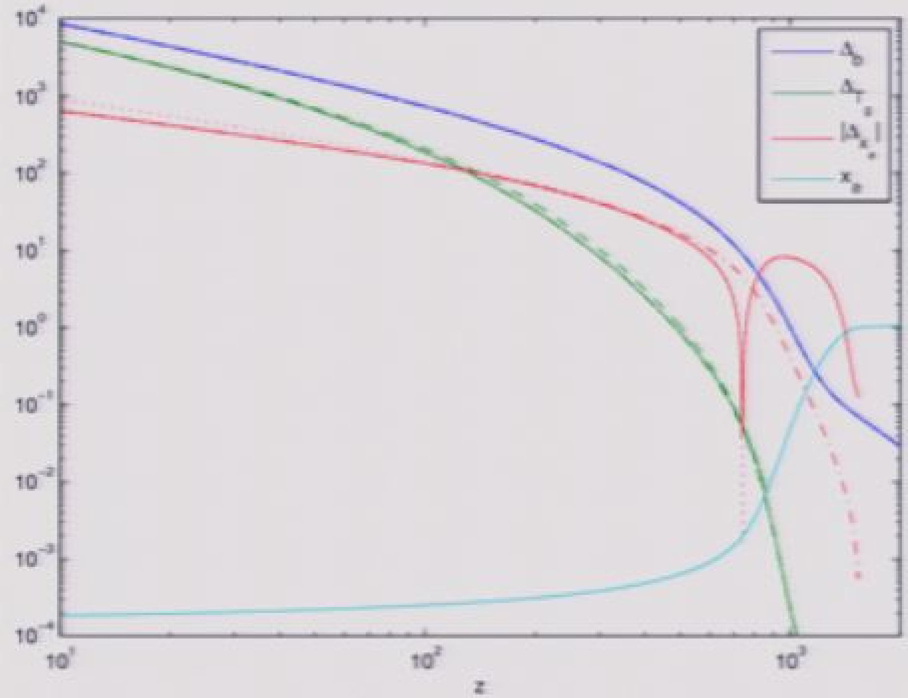
- Temperature perturbation depends on Δ_{x_e}

- Need to model perturbed recombination (this is a LINEAR effect)

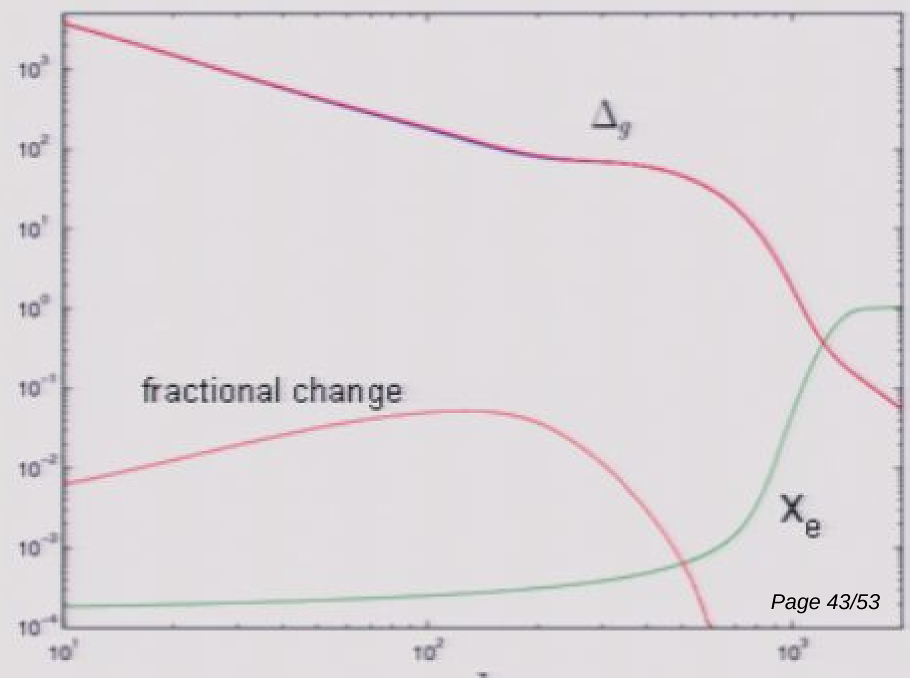
New version of CAMB sources code soon… http://camb.info/sources

(though even unperturbed recombination not yet understood at sub-percent level) e.g. evolution of temperature and x_e perturbations for k=10/Mpc

- important for 21cm predictions on all scales; ~ 2% effect on C_l



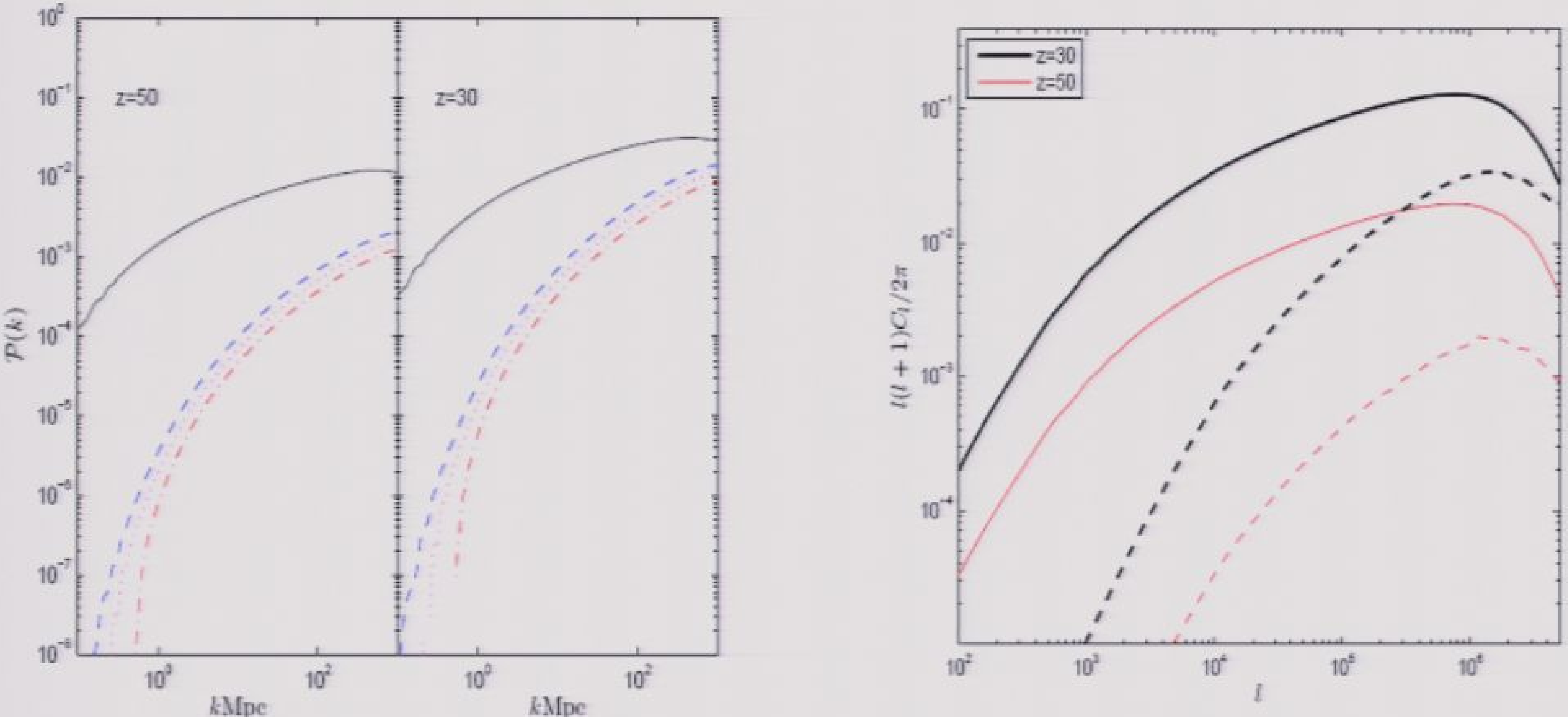
e.g. effect of perturbed x_e on baryon evolution at k=1000/Mpc



Non-linear evolution

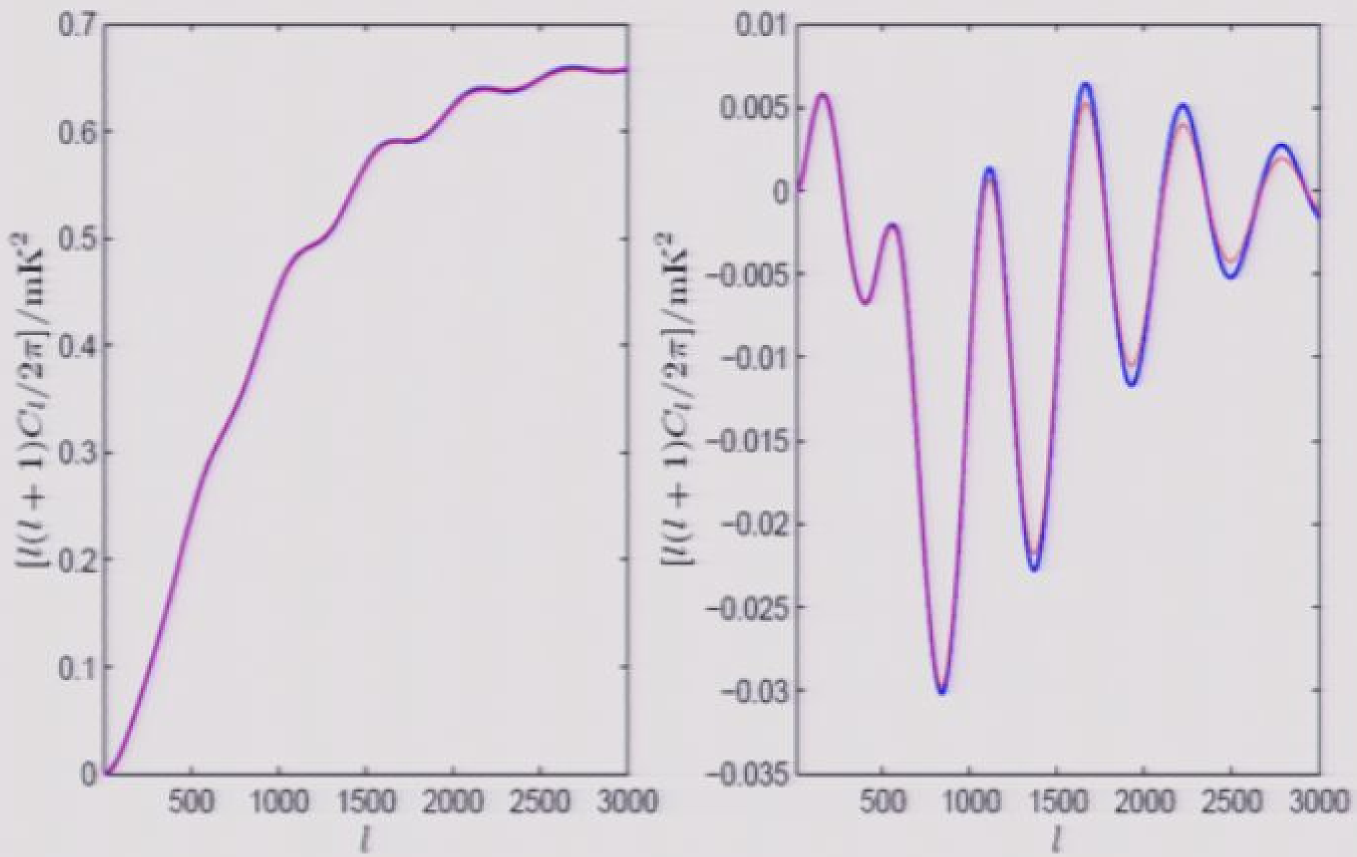
Small scales see build up of power from many larger scale modes - important

But probably accurately modelled by 3rd order perturbation theory:



On small scales non-linear effects many percent even at z ~ 50

Also lensing: like convolution with deflection angle power spectrum; generally small effect as 21cm spectrum quite smooth



$C_l(z=50,z=50)$ $C_l(z=50,z=52)$

Lots of information in 3-D (Zahn & Zaldarriaga 2006)

Observational prospects

No time soon…

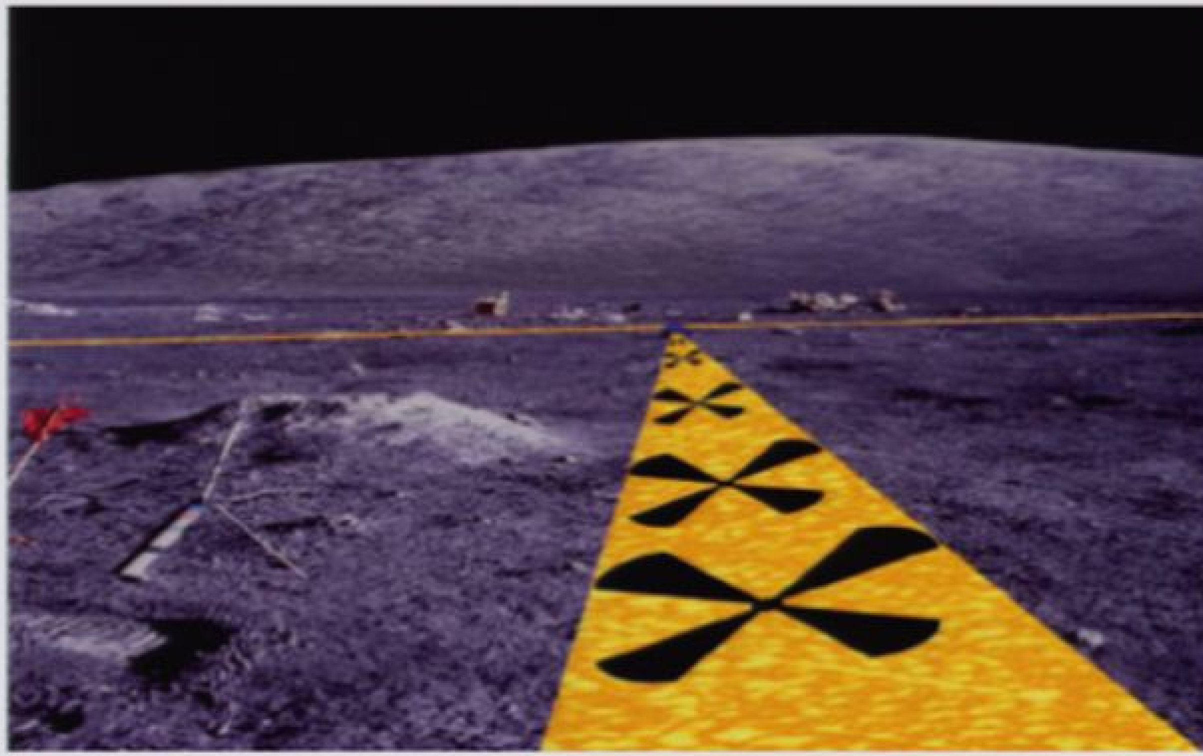
- (1+z)21cm wavelengths: ~ 10 meters for z=50
- atmosphere opaque for z>~ 70: go to the moon?
- fluctuations in ionosphere: phase errors: go to moon?
- interferences with terrestrial radio: far side of the moon?
- foregrounds: large! use signal decorrelation with frequency

But: large wavelength -> crude reflectors OK

See e.g. Carilli et al: astro-ph/0702070, Peterson et al: astro-ph/0606104

Current 21cm:

LOFAR, PAST, MWA: study reionization at z <20
SKA: still being planned, z< 25



RADIO DAYS. Future astronauts lay out a carpet of simple dipole antennas, embedded in plastic, that will hunt for radio signals associated with the first stars in the universe.
NASA Goddard

Things you could do with precision dark age 21cm

- High-precision on small-scale primordial power spectrum
  (n_s, running, features [wide range of k], etc.)
  e.g. Loeb & Zaldarriaga: astro-ph/0312134, Kleban et al. hep-th/0703215

  Varying alpha: $A_{10} \sim \alpha^{13}$
  (21cm frequency changed: different background and perturbations)
  Khatri & Wandelt: astro-ph/0701752
- Isocurvature modes
  (direct signature of baryons; distinguish CDM/baryon isocurvature)
  Barkana & Loeb: astro-ph/0502083
- CDM particle decays and annihilations
  (changes temperature evolution)
  Shchekinov & Vasiliev: astro-ph/0604231, Valdes et al: astro-ph/0701301
- Primordial non-Gaussianity
  (measure bispectrum etc of 21cm: limited by non-linear evolution)
  Cooray: astro-ph/0610257, Pillepich et al: astro-ph/0611126
- Lots of other things: e.g. cosmic strings, warm dark matter, neutrino masses, early dark energy/modified gravity….

e.g.

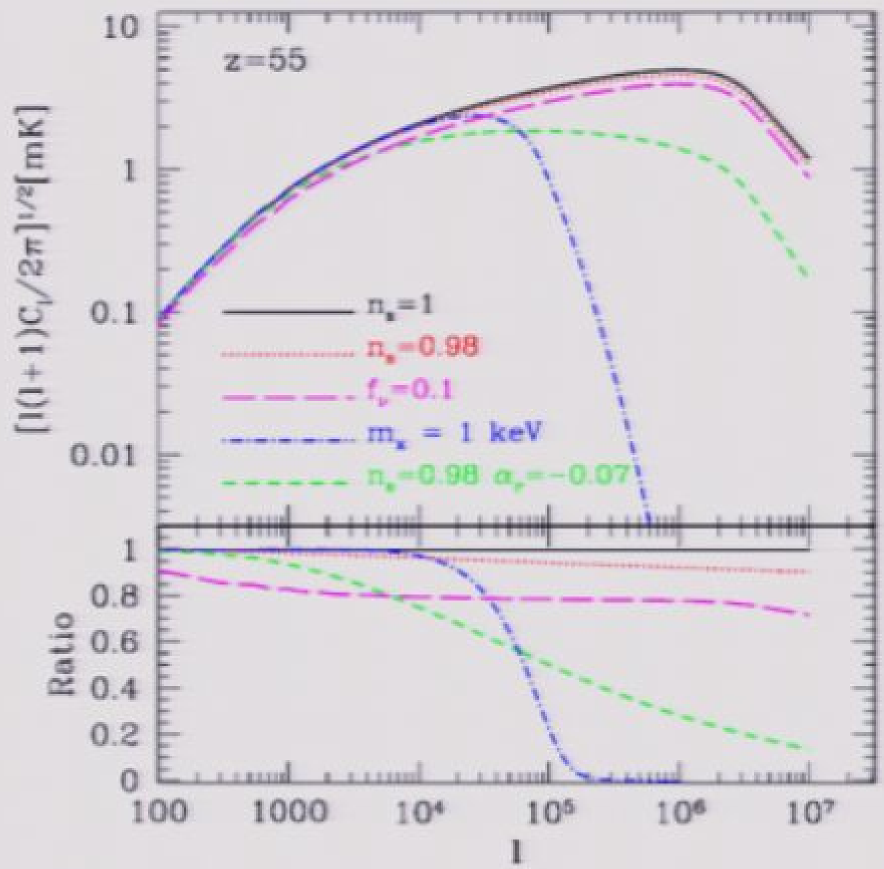


FIG. 3. *Upper panel:* Power spectrum of 21cm anisotropies at $z = 55$ for a ΛCDM scale-invariant power spectrum, a model with $n = 0.98$, a model with $n = 0.98$ and $\alpha_r \equiv \frac{1}{2}(d^2 \ln P/d \ln k^2) = -0.07$, a model of warm dark matter particles with a mass of 1 keV, and a model in which $f_\nu = 10\%$ of the matter density is in three species of massive neutrinos with a mass of 0.4 eV each. *Lower panel:* Ratios between the different power spectra and the scale-invariant spectrum.

Conclusions

- Huge amount of information in dark age perturbation spectrum
  - could constrain early universe parameters to many significant figures
- Dark age baryon perturbations in principle observable at $30<z<500$ up to $l<10^7$ via observations of CMB at $(1+z)$21cm wavelengths.
- Not very much new information on large scales
- Need to carefully model temperature and x_e perturbations
- Very small polarization
- Non-linear effects important even at $z \sim 50$
- Very challenging to observe (e.g. far side of the moon)
- If you can do it, can learn a lot so may be worth the effort!

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Do we need conventional journals?

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Conclusions

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